MEASUREMENT OF THE $Z/\gamma^* \to e^+e^- + \geq n$ JETS PRODUCTION CROSS SECTION AT THE TEVATRON

DRAFT v1.1

BY

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THESIS

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To ... (dedication)

ACKNOWLEDGMENTS

I want to thank ... ... the DØ Collaboration (see Appendix A) ...

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LIST OF ABBREVIATIONS

AA   Alternative Algorithm

BR   Branching Ratio

CC   Central Calorimeter

CellNN   Cell Nearest Neighbor

CDF   Collider Detector at Fermilab

CERN   European Organization for Nuclear Research

CFT   Central Fiber Tracker

CHF   Coarse Hadronic Fraction

CIA   Control, I/O, Address

CKKW   Catani, Krauss, Kuhn, Webber

COOR   Central Coordination Process

CPLD   Complex Programmable Logic Device

CPS   Central Preshower

CPU   Central Processing Unit

CTEQ   Coordinated Theoretical-Experimental Project on

                    QCD

DAQ   Data Acquisition

DEC	Digital Equipment Corporation
DMA	Direct Memory Access
DRAM	Dynamic Random Access Memory
DSW	Data Switch
EC	End Calorimeter
EM	Electro Magnetic
EMF	Electro Magnetic Fraction
FAMUS	Forward Angle Muon System
FIC	Fiber Input Converter
FIFO	First in, First out
FNAL	Fermi National Accelerator Laboratory
FPGA	Field Programmable Gate Array
FPS	Forward Preshower
HotF	Hot Fraction
HTF	Histogramming Track Finder
ICD	Inter Cryostat Detector
ICR	Inter Cryostat Region
IDE	Integrated Drive Electronics

I/O	Input/Output
ISA	Industry Standard Architecture
JES	Jet Energy Scale
L1	Level 1
L1Cal	Level 1 Calorimeter
L1CTT	Level 1 Central Track Trigger
L1Muon	Level 1 Muon
L2	Level 2
L2Cal	Level 2 Calorimeter
L2CTT	Level 2 Central Track Trigger
L2GBL	Level 2 Global
L2MUC	Level 2 Muon Central
L2MUF	Level 2 Muon Forward
L2Muon	Level 2 Muon
L2PS	Level 2 Preshower
L2STT	Level 2 Silicon Track Trigger
L3	Level 3
L3DAQ	Level 3 Data Acquisition

LBN	Luminosity Block Number
Linac	Linear Accelerator
MB	Minimum Bias
MBT	Magic Bus Transceiver
MBus	Magic Bus
MC	Monte Carlo
MCFM	Monte Carlo for FeMtobarn processes
MDT	Mini Drift Tube
MG	Massless Gap
MPM	Multi Port Memory
PCI	Peripheral Component Interconnect
PDF	Parton Distribution Function
PDT	Proportional Drift Tube
PIO	Programmed Input Output
PLD	Programmable Logic Device
PV	Primary Vertex
RF	Radio Frequency
RISC	Reduced Instruction Set Computing

LIST OF ABBREVIATIONS (Continued)

ROM	Read Only Memory
QCD	Quantum Chromo Dynamics
SBC	Single Board Computer
SCL(init)	Serial Command Link (Initialize)
Scone	Simple Cone
SIMM	Single In-line Memory Module
SM	Standard Model
SMT	Silicon Microstrip Tracker
SROM	Serial Read Only Memory
TCC	Trigger Control Computer
TDR	Technical Design Report
TOT	Total Energy
VBD	VME Buffer Driver
VITA	VMEbus International Trade Association
VLPC	Visible Light Photon Counter
VME	VERSA Module Eurocard
WAMUS	Wide Angle Muon System

SUMMARY

We present a study of events with Z bosons and hadronic jets produced at the Tevatron in $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV. The data consist of approximately 14,000 $Z/\gamma^* \to e^+e^-$ decay candidates from 343 pb^{-1} of integrated luminosity collected using the DØ detector. Cross sections and jet production properties have been measured for $Z/\gamma^*+ \geq 0$ to 5 jet events. We find our results to be in good agreement with QCD predictions.

CHAPTER 1

INTRODUCTION

Since the discovery of the Z boson at CERN in 1983 (1), (2), the production of electroweak gauge bosons in association with jets has been of increasing importance. A measurement of the $Z+ \geq n$ jets cross sections provides a good test for our understanding of quantum chromo dynamics (QCD). In addition, hadronic production of the Z boson is a major background to many interesting physics processes, within or beyond the Standard Model (SM). In particular, Higgs searches in channels where Higgs bosons are being produced in association with Z bosons (*Higgs Strahlung*) depend on a precise knowledge of the $Z+ \geq 2$ jets cross section.

Chapter 2 of this dissertation provides a short overview of the theoretical framework within which this study is performed. A description of the experimental apparatus, including the Fermilab chain of accelerators, and the DØ detector is given in Chapter 3. The data and Monte Carlo (MC) samples that were used are illustrated in Chapter 4. Chapter 5 outlines all steps that lead to the $Z+ \geq n$ jets cross section measurement. A brief summary of the final result, together with a discussion of future plans, is given in Chapter 6.

Throughout this dissertation we follow the customary convention by which $\hbar = c = 1$.

CHAPTER 2

THEORY

2.1   The Standard Model

The *Standard Model of Particle Physics* is the name given to the current theory of elementary particles and the forces that act between them. It is a quantum theory of fields (QFT), which arises when combining quantum mechanics with special relativity. The SM includes most of our current understanding of the laws of physics (except gravity), and has been verified experimentally to an extremely high level of accuracy.

Nevertheless, the theory is incomplete. The SM contains many free parameters that can't be derived from first principles. The Higgs Boson, which is considered to be the last remaining piece to the SM, still hasn't been experimentally detected. Most importantly, gravity is not included in the SM. A framework that consistently combines quantum mechanics with general relativity into a theory of *quantum gravity* hasn't been discovered yet.

The following is a brief overview of the SM together with the particles and interactions that it describes.

2.1.1   Quarks and Leptons

In the SM the most fundamental particles that make up ordinary matter are divided into two groups: *quarks* and *leptons* (Figure 1, Reference (3)). Both quarks and leptons are *fermions* since they are spin-$\frac{1}{2}$ particles, and therefore obey Fermi-Dirac statistics. As indicated in

Figure 1, quarks and leptons are each arranged in three families, each family being identical except for the masses of its members. For each particle there exists an anti-particle with opposite charge.

There are six different types of quarks, labeled (in order of increasing mass) *up*, *down*, *strange*, *charm*, *bottom*, and *top*. It is remarkable to note that quarks are never observed as single particles (see Chapter 2.1.2.3), and that they carry fractional electrical charges[1] of $+\frac{2}{3}$ or $-\frac{1}{3}$e. Quarks form bound states called *hadrons* by either combining three quarks into *baryons*, or by pairing a quark with an antiquark into *mesons*. Protons (made up of *u-u-d* quarks) and neutrons (made up of *d-d-u* quarks) are the most common examples for baryons. Pions ($\pi^{0,\pm}$) and Kaons ($K^{\pm}$, K^0, $\bar{K}^0$) are the most common examples for mesons.

There are three different types of charged leptons, carrying -1e of electrical charge: *electrons* (e^-), *muons* (μ^-), and *tau leptons* (τ^-). While electrons exist in all atoms, muons and tau leptons can only be observed in energetic processes like cosmic ray showers, or high energy particle collisions. There are three neutral leptons, called *neutrinos* (ν), each corresponding to a charged lepton: ν_e, ν_μ, and ν_τ.

2.1.2 <u>Interactions</u>

One of the most fundamental insights in theoretical physics is that interactions are dictated by symmetry principles (4). In QFT interactions manifest themselves by imposing symmetry conditions on the quantum fields representing the respective interactions. Using the framework

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[1]All charges are given in unites of the absolute value of the electron charge, 1.602×10^{-19} Coulombs.

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

Figure 1. Quarks and leptons.

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
				Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Figure 2. Properties of the interactions.

of Lagrangian field theory, we impose that the Lagrangian of the theory be invariant under a group of local phase changes (*local gauge invariance*). A local phase change means that the phase change depends on space and time in a completely arbitrary way. The Langrangian is no longer invariant under such local phases changes. In order to preserve gauge invariance of the Lagrangian (on purely aesthetic grounds) we introduce an additional gauge field. Excitations of these gauge fields lead to force-carrying spin-1 bosons that mediate the interactions of nature.

Four types of interactions are currently known (in order of decreasing strength): strong, electromagnetic, weak, and gravitational. Figure 2 summarizes basic properties of the four interactions (3). Note that gravity hasn't been incorporated into the SM, since no QFT for gravitational interactions has been discovered yet. Additionally, gravity is simply too weak to have any significant influence on particle interactions.

2.1.2.1 Electromagnetic Interaction

Historically, the electromagnetic interaction was the first to be formulated in the framework of a QFT by Tomonaga, Feynman, and Schwinger in the 1940s (Nobel Prize in 1965). All subsequent efforts to create theories for other interactions are modeled on it. *Quantum Electrodynamics* (QED) describes the electromagnetic interaction by requiring gauge invariance under U(1) group transformations. U(1) denotes a group of unitary one-dimensional matrices, describing space-time dependent rotations in a complex plane. The requirement of gauge invariance gives rise to the photon field and the *photons* as the corresponding mediator of the electromagnetic interaction. Because the photon is massless the interaction is long range. The photon couples to all particles that carry electrical charge, like quarks and charged leptons. The strength of the coupling is proportional to the magnitude of the dimensionless *finestructure coupling constant*:

$$\alpha_{EM} = \frac{e^2}{4\pi} \approx \frac{1}{137} \tag{2.1}$$

2.1.2.2 Weak Interaction

2.1.2.3 Strong Interaction

2.1.3 Electro-Weak Symmetry Breaking

Higgs/Schmiggs

References: (5) (6) (7) (8)

CHAPTER 3

EXPERIMENTAL APPARATUS

The Fermi National Accelerator Laboratory (FNAL, or Fermilab) currently operates the world's highest energy proton-antiproton collider, the Tevatron. In this chapter we describe the chain of accelerators that is necessary to achieve a center-of-mass collision energy of 1.96 TeV. We also give an overview of the DØ detector which is built around one of the collision regions where protons and antiprotons collide.

The data used in this analysis was recorded with the DØ detector during the data taking period known as Run II, which officially began in March 2001.

3.1 The Fermilab Accelerators

The Tevatron is the final stage in a sequence of seven accelerators (9), (10), (11). A Cockcroft-Walton preaccelerator, a linear accelerator (Linac) and a synchrotron (Booster) provide a source of 8 GeV protons. The antiproton Debuncher and Accumulator are two components of the Antiproton Source. The Main Injector serves as the final boosting stage before injecting protons and antiprotons into the Tevatron. It also provides the necessary source of energetic protons which are needed in the Antiproton Source.

Figure 3 gives an overview of the Fermilab accelerator complex (12).
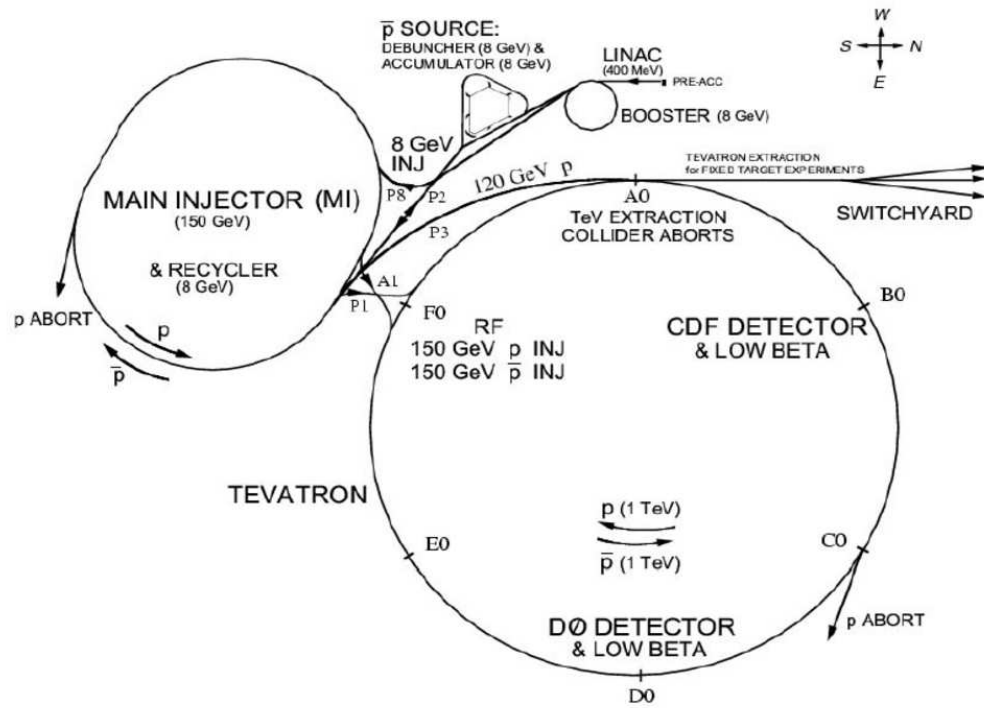
Figure 3. Schematic view of the Fermilab accelerator chain.

3.1.1   The Preaccelerator

The purpose of the preaccelerator is to produce negatively charged hydrogen ions (H^-) with an energy of 750 keV, which are then transfered into the Linac.

Hydrogen gas (H_2) enters a magnetron surface-plasma source (Figure 4). Due to the electric field between the anode (negatively charged) and cathode (positively charged) the electrons are stripped away from the hydrogen atoms to create a plasma. The positively charged hydrogen ions then strike the surface of the cathode to collect extra electrons and thereby form negatively charged hydrogen ions. The H^- ions are extracted through the anode aperture with an electric field of 18 kV applied by the extractor plate (see Figure 4).

A commercial Cockcroft-Walton Generator produces a 750 kV potential differential by charging capacitors in parallel from an AC voltage source and discharging them in series, via diodes [1]. The Cockcroft-Walton Generator is used to further accelerate the H^- ions to an energy of 750 keV.

After exiting the Cockcroft-Walton device the H^- ions travel through a transfer line. Before entering into the Linac the continuous stream of H^- ions passes through a single gap radio frequency (RF) cavity which bunches the beam at the RF frequency of the Linac.

3.1.2   The Linac

The Linac receives bunches of 750 keV H^- ions from the preaccelerator and accelerates them further to an energy of 400 MeV using RF cavities (Figure 5). The RF cavities are contained

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[1]The maximum voltage is limited by how much the air can "stand off" before sparking.
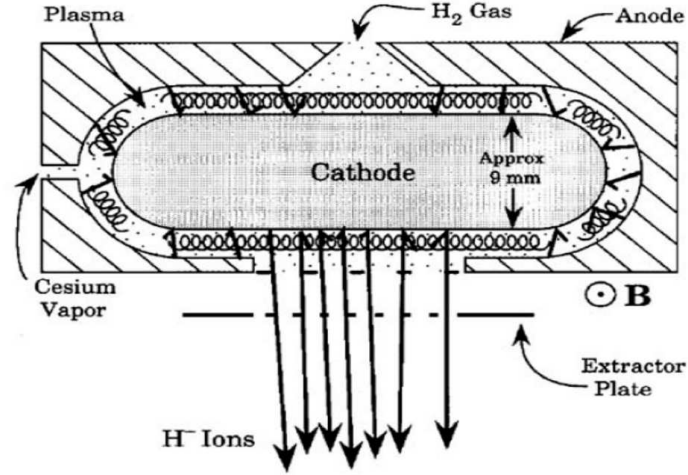
Figure 4. Basic configuration of a magnetron.

within a collection of steel tanks which are holding a sequence of drift tubes separated from each other by gaps. In order to accelerate H$^-$ ions the cavities are designed in such a way that particles traveling in the gaps experience an acceleration, while particles traveling in the drift tubes are shielded from the RF.

After passing through the Linac, bunches of 400 MeV H$^-$ ions are transfered into the Booster.

3.1.3 The Booster

The Booster is the first synchrotron in the chain of acceleration. It consists of a sequence of dipole and quadrupole magnets and 17 RF cavities arranged in a circle with a diameter of 151 m. The Booster accelerates protons to an energy of 8 GeV.
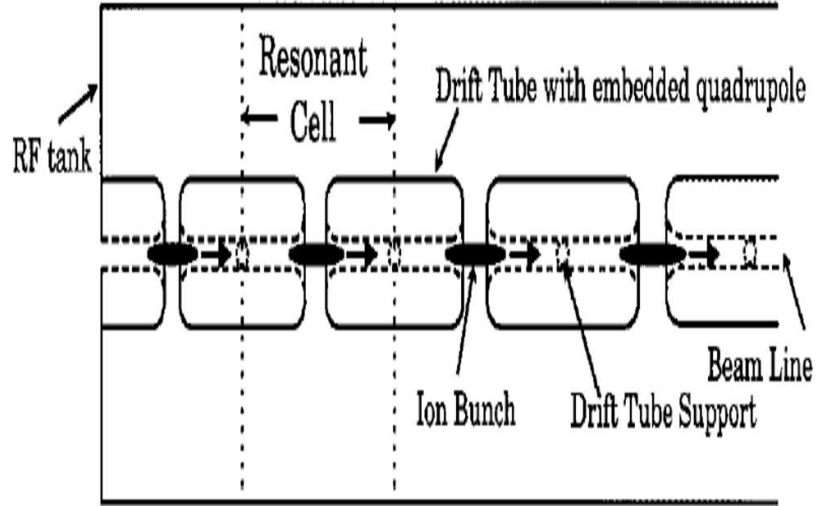
Figure 5. Schematic of Linac RF cavity.

It is easier to merge negatively charged H ions coming from the Linac with protons (H^+ ions) circulating in the Booster due to their opposite charge. Therefore the two beams are merged with the help of dipole magnets and the electrons are stripped from the H^- ions by letting the combined beam pass through a carbon foil.

Once the Booster is filled with proton bunches the RF cavities provide an acceleration up to 8 GeV. At the same time the field strength in the dipole magnets is adjusted accordingly in order to maintain a constant radius for the circulating particles. Once the protons have reached an energy of 8 GeV they are transfered into the Main Injector.

3.1.4   The Main Injector

The Main Injector is a circular synchrotron with a diameter of 1 km. It can accelerate both protons (coming from the Booster) and antiprotons (coming from the Antiproton Source) from 8 GeV to 150 GeV, before injecting them into the Tevatron. It also delivers 120 GeV protons to the Antiproton Source.

Historically the Main Injector was built for Run II in order to replace the Main Ring. The fact that both the Main Ring and the Tevatron occupied the same tunnel led to several problems. First, overpasses for the DØ and CDF detectors had to be built for the Main Ring. Second, due to their close proximity the Tevatron beam was influencing the Main Ring beam. Consequently the Main Injector was built next to the Tevatron using a separate tunnel.

3.1.5   The Antiproton Source

The Antiproton Source consists of three major components: the Target Station, the Debuncher, and the Accumulator. In the first step the Target Station receives 120 GeV protons from the Main Injector and diverts them onto a Nickel Target. This produces a shower of secondary particles (including antiprotons) at many different angles and large spread in particle momentum. A Lithium lens and bending magnets are used to focus the beam and remove positively charged particles (Figure 6, and Reference (13)). A process called *stochastic cooling* is used in both the Debuncher and Accumulator in order to reduce the spread in momentum and position of the antiprotons and thereby "cooling" them.

Both the Debuncher and Accumulator are located in a rounded-triangle shaped tunnel with a circumference of about 51 m. Antiprotons coming from the Target Station are transfered
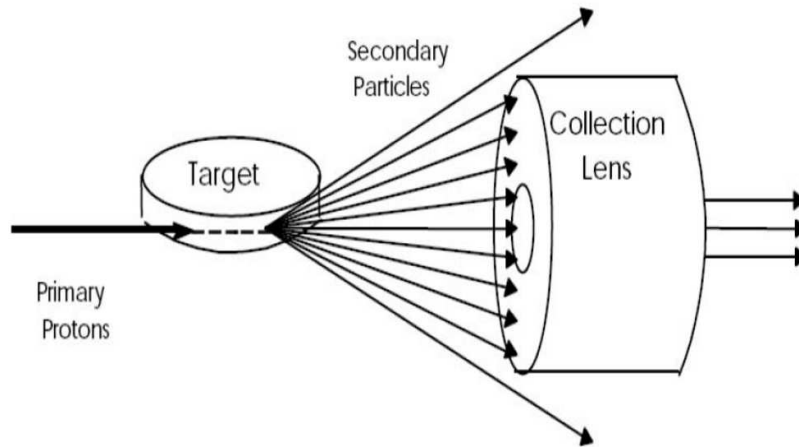
Figure 6. Simplified drawing of anti-proton production with nickel target and lithium lense.

into the Debuncher where the momentum spread of the particles is reduced. It is technically very challenging to accumulate a large quantity of antiprotons. On average for every 1 million protons that hit the Nickel target, only about 20 antiprotons can be gathered. Therefore the Accumulator stores antiprotons till a sufficient amount has been generated that can be transfered into the Main Injector. The Accumulator must be capable of storing antiprotons over many hours.

3.1.6 The Tevatron

The Tevatron is the final stage in the sequence of proton and antiproton acceleration. It has a diameter of 2 km and uses superconducting magnets which operate at liquid helium

temperature providing magnetic fields of up to 4 T. Protons and antiprotons are accelerated to

980 GeV, leading to a center-of-mass collision energy of 1.96 TeV.

36 bunches of protons and antiprotons travel in opposite directions and share the same

beam pipe. Collisions occur every 396 ns at the DØ interaction point.

3.2   Luminosity and Cross Section

Luminosity $\mathcal{L}$ is a measure of particle flux per unit area and per unit time ($\text{cm}^{-2}\text{s}^{-1}$). In a

collider experiment such as DØ it gives an indication of how many proton-antiproton collisions

(events) occur in a given time and area. The luminosity is determined by measuring the rate

of inelastic proton-antiproton scatterings, which have a known cross section (14).

The cross section σ is a measure of the interaction probability per unit flux. Cross sections

are usually expressed in *barns*, where 1 barn = 10^{24} cm^2.

The number of times a given process occurs, N, is proportional to $\mathcal{L}$ and σ:

$$N = \sigma \cdot \int \mathcal{L} \, dt \tag{3.1}$$

$\int \mathcal{L} \, dt$ is called *integrated luminosity*. Figure 7 shows the integrated luminosity profile of the

Tevatron, covering the data-taking period from April 2002 till March 2005. A total integrated

luminosity of 343 pb^{-1} was used for the result presented in this analysis.

3.3   The DØ Detector

The DØ detector (Figure 8, and References (15), (16)) has a magnetic central-tracking sys-

tem, consisting of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both
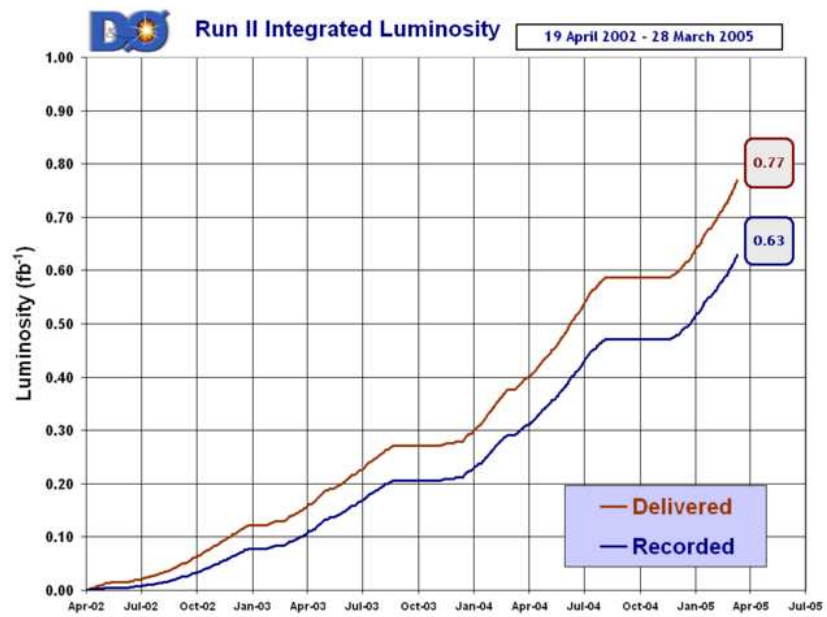
Figure 7. Tevatron integrated luminosity delivered to DØ (April 2002 - March 2005).

located within a 2 T superconducting solenoidal magnet. Central and forward preshower detectors are located just outside of the superconducting coil. A liquid-argon/uranium calorimeter has a central section (CC) covering pseudorapidities $|\eta|$ up to ≈ 1, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$, all three housed in separate cryostats. A muon system resides beyond the calorimetry, and consists of a layer of tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two more similar layers after the toroids. Luminosity is measured using plastic scintillator arrays located in front of the EC cryostats. The trigger and data acquisition systems are designed to accommodate the high luminosities of Run II.

3.3.1   Coordinate Systems

The coordinate system used for the DØ detector is right-handed. It has the positive z-axis aligned with the direction in which the protons travel and the positive y-axis pointing upwards.

In most cases cylindrical coordinates are used (z, Φ, θ). Φ is the azimuthal angle in the plane perpendicular to the beam (z-axis), where $\Phi=0$ coincides with the positive x-axis. θ is the polar angle relative to the positive z-axis.

Since the colliding protons and antiprotons can exhibit a significant net boost along the z-axis it is suitable to choose a polar angle quantity that is invariant under relativistic transformations. Therefore it is often more convenient to use pseudorapidity η instead of the polar angle θ:

$$\eta = -ln \cdot \left[tan\frac{\theta}{2} \right] \tag{3.2}$$
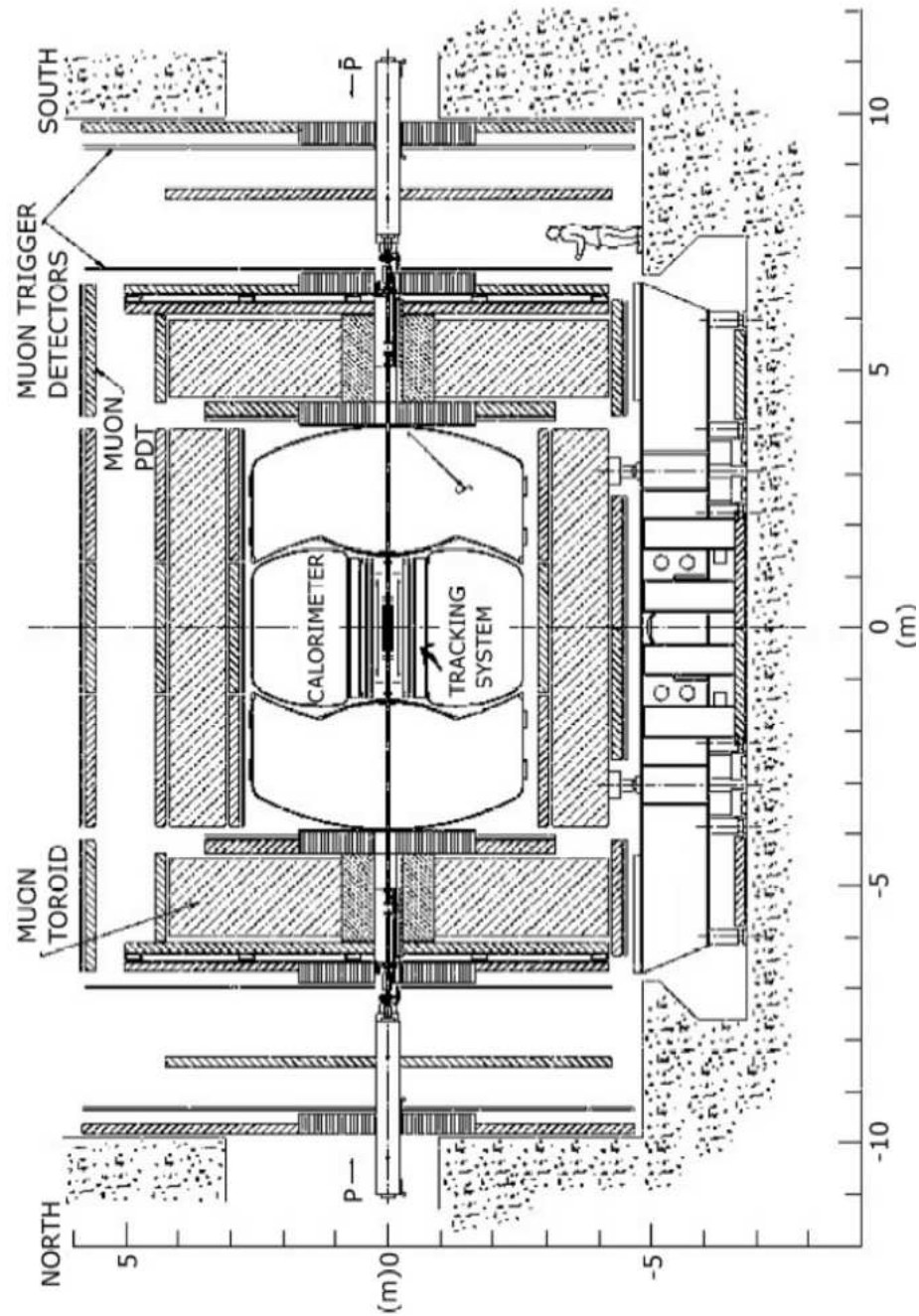
Figure 8. Schematic view of the DØ detector.

The pseudorapidity approximates the true rapidity,

$$y = \frac{1}{2} \cdot ln\left[\frac{E + p_z}{E - p_z}\right] \qquad (3.3)$$

in the limit of $m \ll E$ (where m is the invariant mass $m^2 = E^2 - p^2$). We use the term "forward" to describe regions at large $|\eta|$.

In many cases some of the products of a proton-antiproton collision escape along the beam pipe which makes it difficult to measure momentum components along the z-axis accurately. Therefore it is more convenient to use the momentum vector projected onto a plane perpendicular to the beam axis (*transverse momentum*):

$$p_T = p \cdot sin\theta. \qquad (3.4)$$

In a similar fashion we define *transverse energy* as

$$E_T = E \cdot sin\theta. \qquad (3.5)$$

3.3.2   Central Tracking System

The central tracking system is essential in measuring the position of the primary interaction vertex with high accuracy, which subsequently allows good measurement of lepton p_T, jet E_T and missing transverse energy ($\not{E}_T$). It also allows to detect the presence of b-quarks through the measurement of displaced vertices.
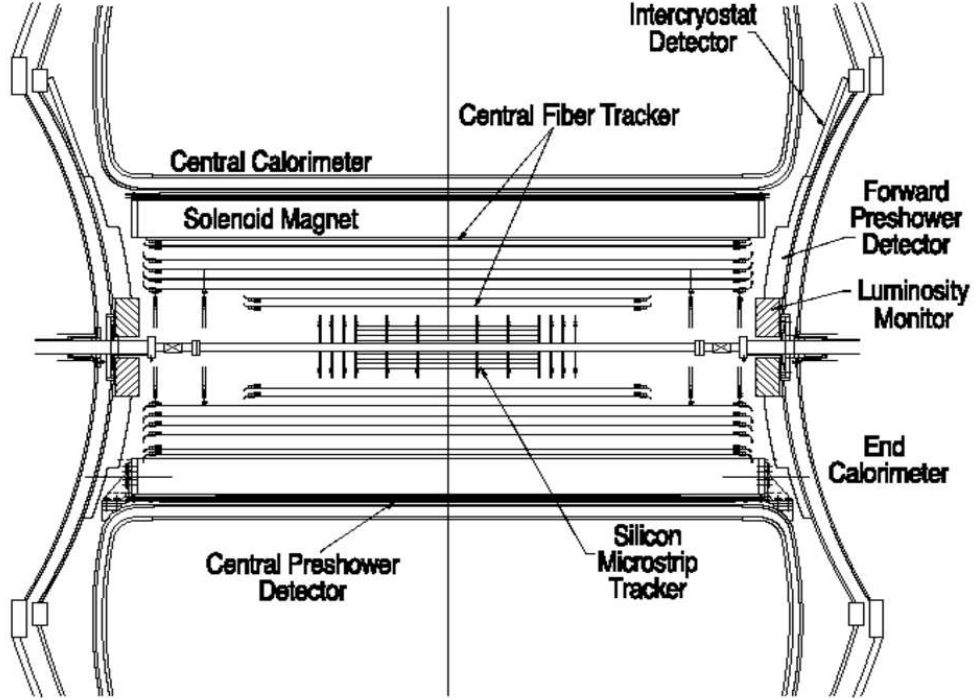
Figure 9. The DØ central tracking system with with solenoid, preshower detectors, luminosity monitor, and calorimeter.

The Central Tracking System consists of the silicon microstrip tracker (SMT), the central fiber tracker (CFT) and the superconducting solenoid (Figure 9). Combining information from both SMT and CFT the primary vertex resolution is approximately 35 μm along the beamline. Jets originating from the decay of b-quarks can be measured with an impact parameter resolution of less than 15 μm in $r - \Phi$.

3.3.2.1 Silicon Microstrip Tracker

In order to be able to detect the paths of charged particles emerging from a proton-antiproton collision, the SMT (17) uses wavers of silicon with a thickness of 300 μm. When a charged particle passes through a p-n junction in silicon it produces electron-hole pairs that can be separated by an applied voltage. The charge which is collected can then be stored in capacitors and later read-out and digitized. The SMT contains a total of approximately 800,000 individual silicon detectors. Figure 10 shows the design of a basic silicon detector unit (*ladder*).

The SMT is designed in such a way that tracks of charged particles are perpendicular to detector material over a large range of η values. The structure of the device is mostly dictated by the fact that the interaction region is spread out with respect to the center of the detector ($\sigma \approx 25$ cm). This leads to a design of barrel modules combined with disks in the center and larger disks in the forward region (Figure 11). The SMT has six barrels along the z-axis, each containing four detector layers with a maximal outer radius of 10.5 cm. There are twelve small diameter double-sided "F" disks and four large diameter single-sided "H" disks to cover the far forward region ($|\eta| <$3). The F-disks are at $|z| = 12.5, 38.2, 43.1$ and 53.1 cm. The centers of the H-disks are located at $|z| = 100.4, 121.0$ cm.

3.3.2.2 Central Fiber Tracker

The Central Fiber Tracker (CFT) (18) is located in between the SMT and the solenoid magnet. The purpose of the CFT is to improve the detection of charged particle tracks within $|\eta| < 2$. It consists of approximately 70,000 scintillating fibers mounted on eight concentric support cylinders with inner and outer radii of 20 and 52 cm, respectively. Each cylinder
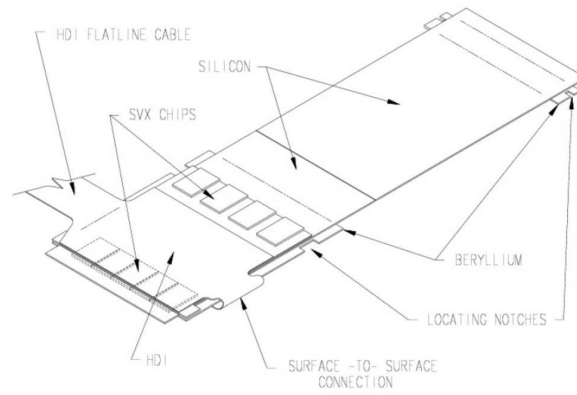
Figure 10. Double-sided ladder design, n-side.
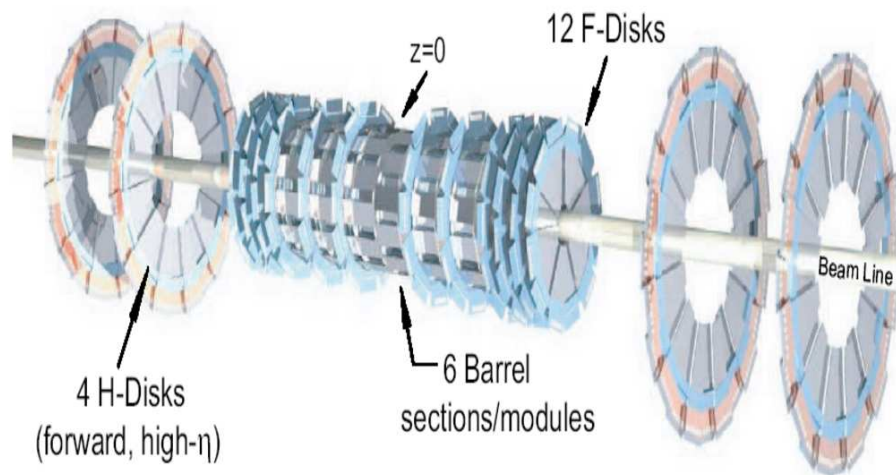
Figure 11. SMT disk and barrel design.

carries two layers of fibers running parallel to the beampipe (*axial layers*), and two layers of fibers oriented at small angles of $\pm 3°$ (*stereo layers*) (Figure 12). The scintillating fibers have a diameter of 835 μm and are composed of a scintillating core surrounded by a layer with a high index of refraction, which leads to total internal refraction.

Charged particles passing through a scintillating fiber excite the molecules in the fiber which subsequently release photons in the yellow-green part of the visible light spectrum as they relax to their ground states. Clear fiber waveguides carry the scintillation light to visible light photon counters (VLPCs) that convert the light into electrical signals. The VLPCs are silicon avalanche photodetectors that operate at liquid helium temperature in order to reduce the background due to electronic noise.

3.3.2.3   Solenoidal Magnet

The superconducting solenoidal magnet significantly improves the capabilities of the DØ detector with regard to the detection of charged particle tracks and momentum resolution. The location and physical size of the magnet are constrained by the available space between the inner tracking system and the vacuum vessel of the central calorimeter. The magnet has a length of 2.73 m and a diameter of 1.42 m and provides uniform field of 2 T (20 kG) over most of the region covered by the inner tracking system (Figure 13). Figure 14 shows a perspective view of the solenoid inside the central calorimeter with its chimney and control dewar.

3.3.3   Preshower Detectors

The preshower detectors (19), (20) are designed to improve the identification of electrons and background rejection. By the time a charged particle has reached the preshower detectors
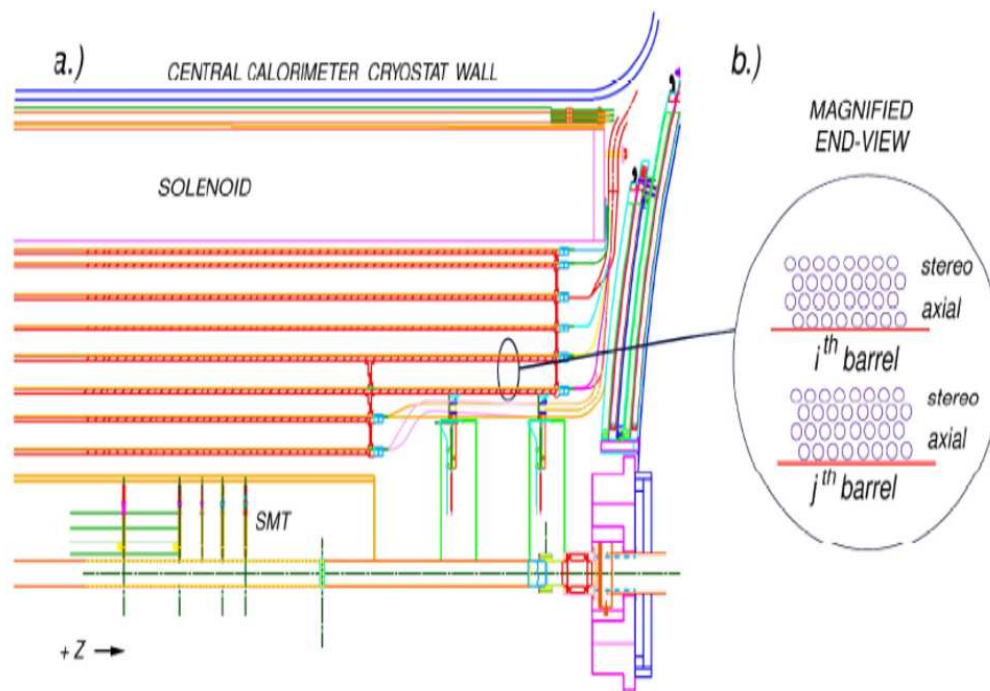
Figure 12. a) Location of the Central Fiber Tracker (CFT). b) Closeup view of axial and stereo layers.
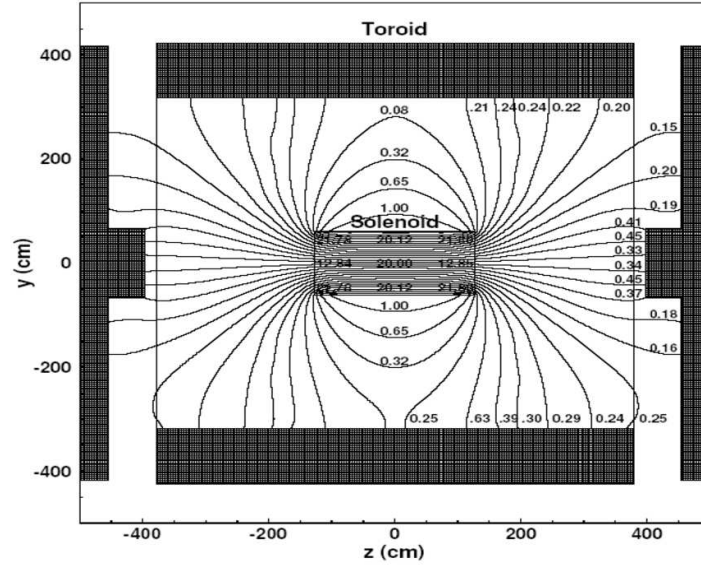
Figure 13. $y - z$ view of the DØ magnetic field with both the toroid and solenoid magnets at full current. Numbers are in kG (10 kG = 1 T).

it has already passed through several detectors as well as other upstream material like cables and support structures. The preshower detectors allow to correct for upstream energy losses in the offline event reconstruction. Due to their fast response time the preshower detectors can also be used for Level 1 triggering (see Chapter 3.4.1).

Scintillators are used to detect both position and energy of charged particles. In contrast to the scintillators used in the CFT, preshower scintillators are triangular shaped (Figure 15). This allows to arrange layers of scintillators without creating any dead space and thereby improving the accuracy of position measurements. The center of each scintillator carries a
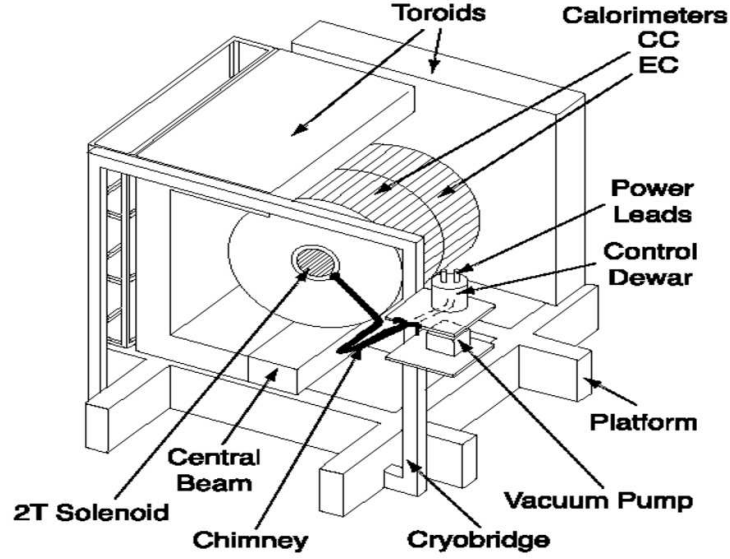
Figure 14. Perspective view of the solenoid inside the central calorimeter.

wavelength-shifting fiber which collects the light created by passing charged particles. The light is transmitted via clear fibers to VLPCs for readout.

3.3.3.1   Central Preshower Detector

The Central Preshower Detector (CPS) is located in the 5 cm gap between the solenoid and the central calorimeter, covering the region $|\eta| < 1.3$ (Figure 9). It consists of a layer of lead radiator which has a thickness corresponding to approximately one radiation-length (X_0), followed by three layers of triangular scintillator strips. The purpose of the lead radiator is to ensure that the total amount of material encountered by a passing particle is constant at all pseudorapidities. The scintillating layers are arranged in an axial-u-v geometry, with a u stereo
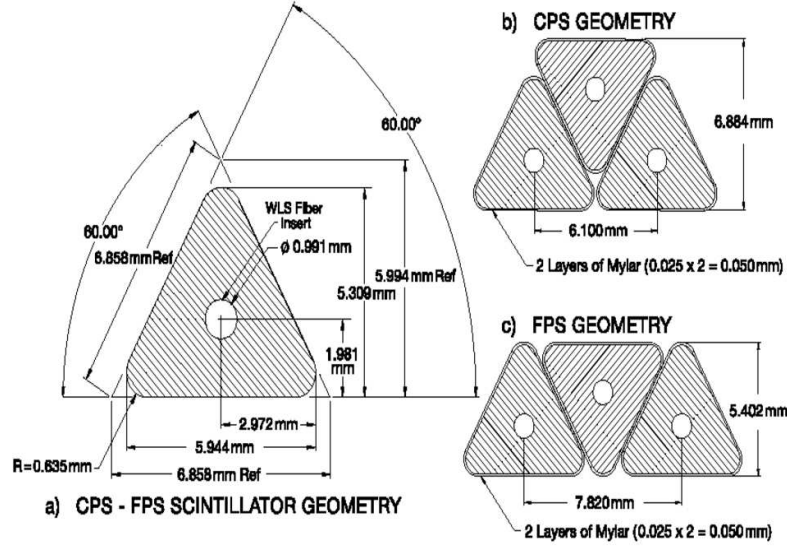
Figure 15. Cross section and layout geometry of the CPS and FPS scintillator strips.

angle of $23.8°$ and a v stereo angle of $24.0°$. Each layer has a total number of 2,560 readout channels.

3.3.3.2   Forward Preshower Detector

The two Forward Preshower Detectors (FPS) are attached to the faces of the end calorimeters and cover a region of $1.5 < |\eta| < 2.5$ (Figure 9). Each detector consists of an upstream double layer of scintillator strips (minimum ionizing particle layers, or MIP layers), followed by a lead-stainless-steel absorber layer, and another double layer of scintillator strips behind it (shower layers). This configuration allows for the distinction between electron-like and photon-like objects. While an electron-like object will create a minimum ionizing energy deposit in the

MIP layers, a photon-like object won't. Therefore electrons can be identified by requiring spatially matched energy deposits in both the MIP layers and the shower layers, whereas photons will only have energy deposits in the shower layers.

3.3.4   Calorimeter

The main purpose of the calorimeter system (21) is to measure the energy deposits from electrons, photons, and jets. It also allows direct identification of electrons, photons, jets, and muons. In addition, measurements of the transverse energy balance in an event, allow to detect the presence of neutrinos.

The calorimeter system consists of a central calorimeter (CC) covering $|\eta| < 1.2$ and two end calorimeters (EC), covering $1.3 < |\eta| < 4.0$ (Figure 16). Each of the calorimeters has an electromagnetic section, followed by fine and coarse hadronic sections. Since liquid argon is used as the active medium, all calorimeters are contained within cryostats. Different types of materials are used for absorber plates:

- 3 mm (4 mm) plates of depleted uranium for the CC (EC) electromagnetic sections.

- 6 mm plates of uranium-nobium (2%) for the fine hadronic sections.

- 46.5 mm plates of copper (stainless steel) for the CC (EC) coarse hadronic sections.

A typical calorimeter cell is shown in (Figure 17). Each cell consists of a grounded absorber plate and a signal board maintained at a positive high voltage of typically 2 kV. The 2.3 mm gap between the absorber plate and signal board is filled with liquid argon. The calorimeter cells are arranged to form pseudo-projective towers (Figure 18).

In order to measure the energy of electromagnetically interacting objects, the calorimeter takes advantage of the electromagnetic shower process. For example, an incoming electron will emit Bremsstrahlung photons when passing through the dense absorber material and interacting with the nuclei in the absorber via Coulomb interaction. The emitted photons will subsequently decay into electron-positron pairs. This chain of processes continues till the energies of the secondary particles fall below the threshold for pair production. After that the particles mainly interact via ionization. At each stage of the electromagnetic shower, charged particles are ionizing the liquid argon. The high voltage between the absorber plates and signal boards is then used to collect the ionization charges, which allows a measurement of the energy in the shower. Typical transverse sizes of electromagnetic showers are in the range of 1-2 cm.

Hadronic showers are induced by the interaction between hadronic particles and the nuclei of the absorber material via the strong nuclear force. Secondary hadronic particles then further interact via inelastic nucleus collisions till their energy falls below a threshold. Typical transverse sizes of hadronic showers are of the order of 10 cm.

The space in between the central and end calorimeters ($1.1 < |\eta| < 1.4$) is referred to as the intercryostat region (ICR). In order to be able to measure the energies of particles that pass through this gap in the calorimeter coverage, additional detectors are used. Calorimeter cells called massless gaps (MG) are installed before the first layer of uranium inside of the central and end cryostats. Additionally, a ring of scintillator tiles mounted to the exterior surface of the end cryostats comprises the intercryostat detector (ICD).

Figure 19 shows the different calorimeter detection layers for a given η value (22).
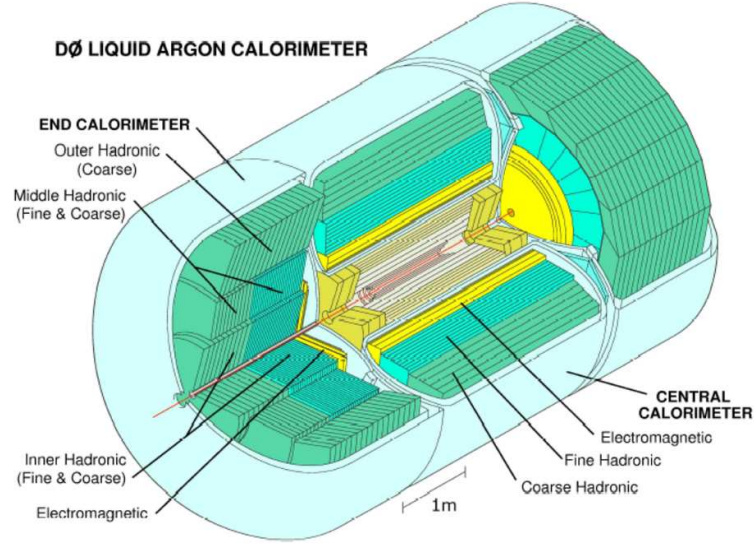
Figure 16. Isometric view of the central and two end calorimeters.

3.3.5   <u>Muon System</u>

Due to their large mass and long lifetime, muons pass through the calorimeter by depositing only a small amount of energy (≈ 2.5 GeV) via ionization. Therefore, the outermost subdetector is dedicated to the detection of muons (Figure 20). The muon system is separated into central and forward detectors. A 1.9 T iron toroid magnet is used for muon momentum measurements.

Proportional Drift Tubes (PDT), Mini Drift Tubes (MDT), and scintillators are the main detection elements used in the muon system. Drift tubes collect the ionization charges created by muons passing through a gas mixture onto high voltage wires. Correlating the arrival times of
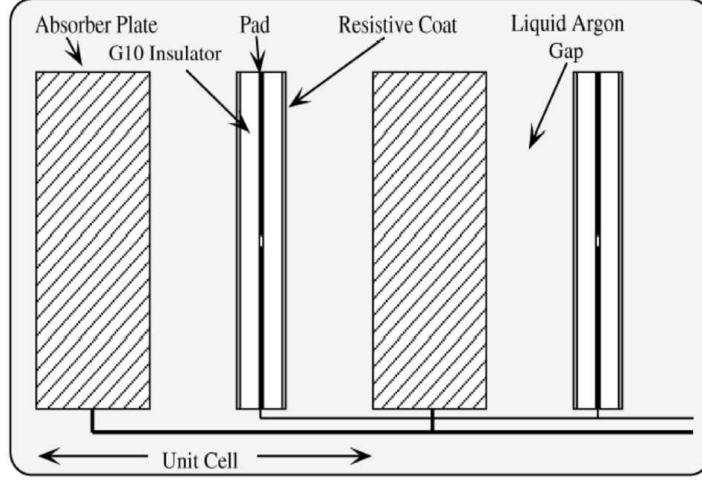
Figure 17. Schematic view of two calorimeter cells.

ionization charges from different drift tubes with the beam crossing time, allows to extrapolate the path of muons as they pass through the detector. Scintillators are mainly used for their good timing resolution ($\approx$ 4 ns) which allows a way to trigger on muons.

The central muon system (23) covers the region of $|\eta| < 1.0$ and is referred to as the Wide Angle Muon System (WAMUS). It consists of three PDT layers, with the first layer (A layer) in between the toroid magnet and the calorimeter, and two more layers (B and C layers) after the toroid magnet. Additional layers of scintillators before the A layer and covering the outside of the muon system allow for spatial and precise timing measurements to reject cosmic rays.

The forward muon system (24) covers the region of $1.0 < |\eta| < 2.0$ and is referred to as the Forward Angle Muon System (FAMUS). It consists of three MDT layers and scintillators, with
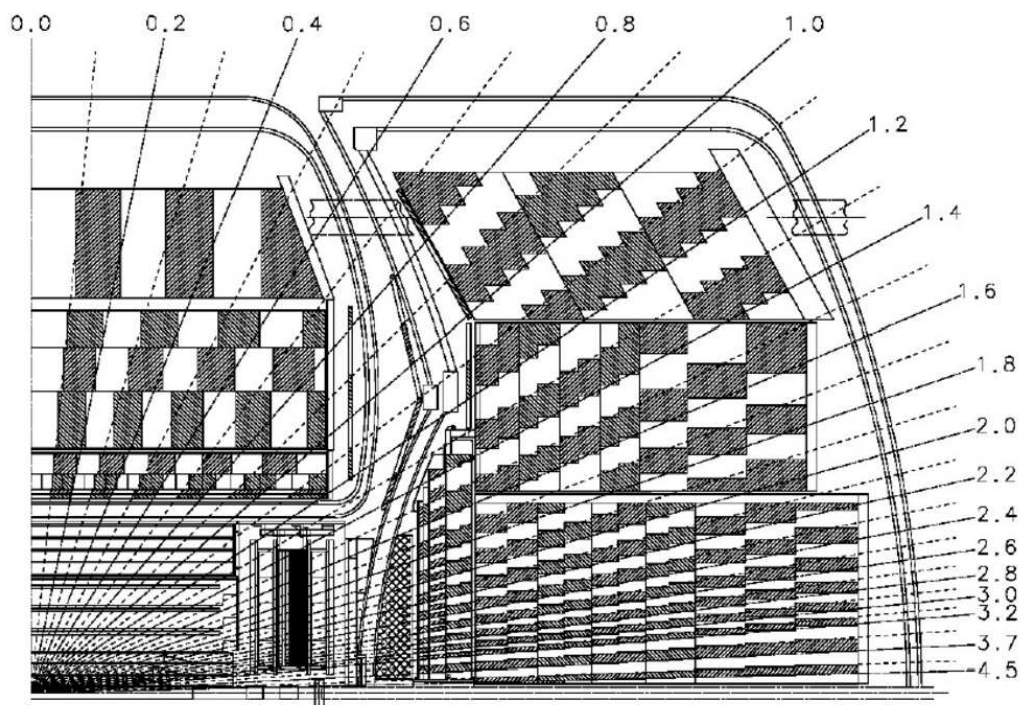
Figure 18. Schematic view showing the calorimeter segmentation pattern. The shading pattern indicates cells for signal readout. The radial lines show the detector pseudo-rapidity intervals.
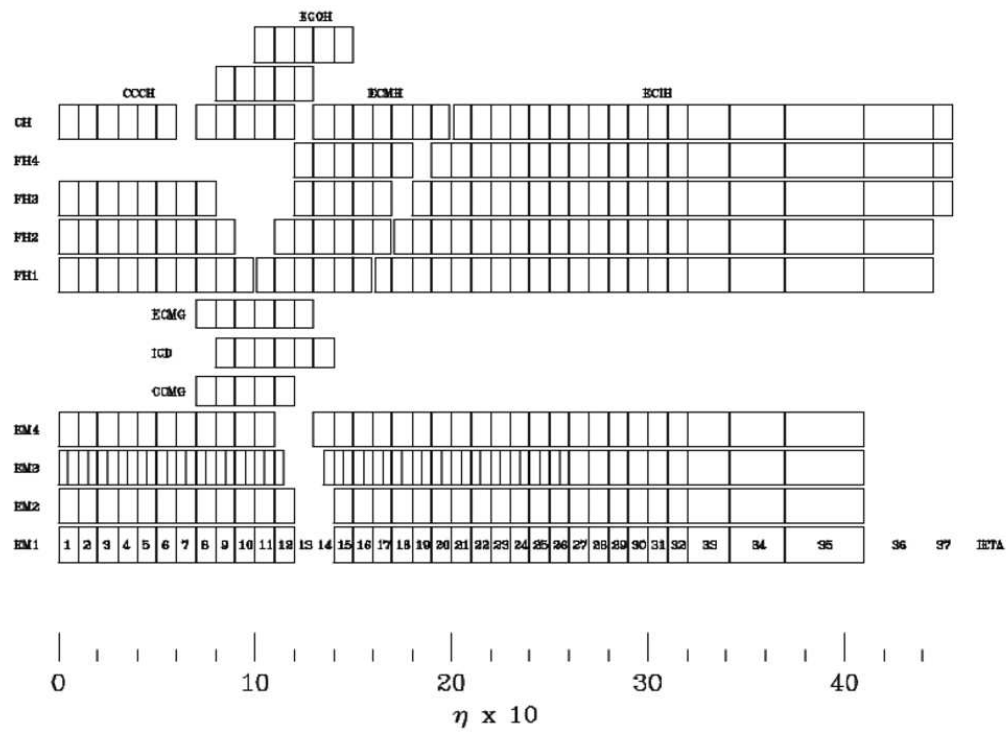
Figure 19. Schematic view of different calorimeter detection layers vs η.
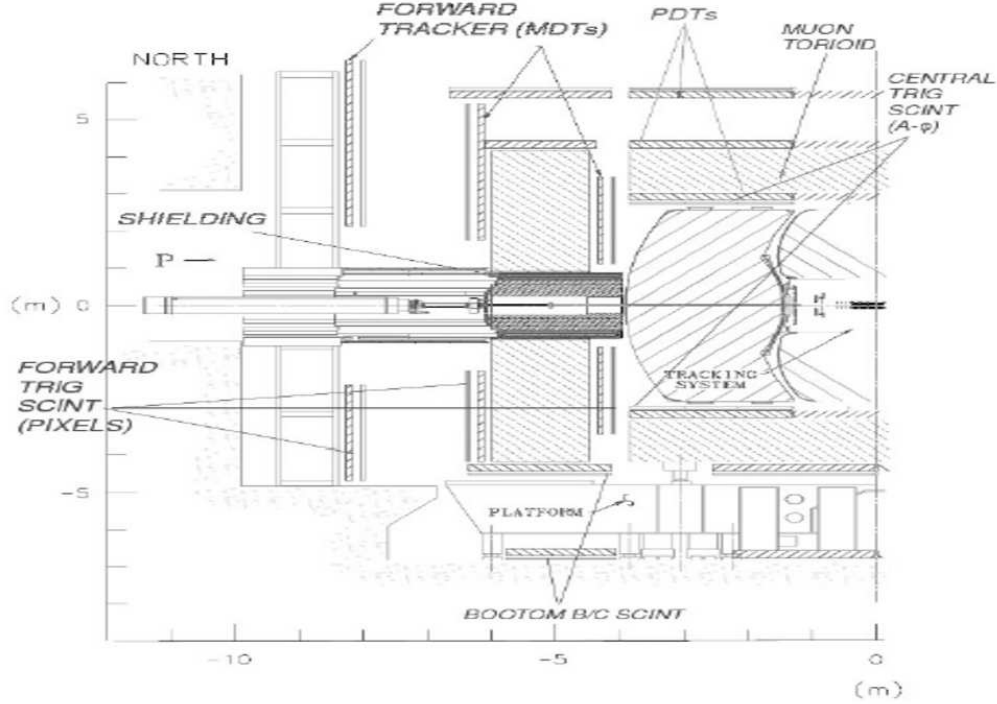
Figure 20. The DØ muon system with scintillators (SCINT) and drift tubes (PDT and MDT).

the first layer (A layer) before the toroid magnet, and two more layers (B and C layers) after
the toroid magnet.

3.4   The DØ Trigger and Data Acquisition Systems

DØ deploys a three level trigger system (25), (26) to handle the high proton-antiproton
collision rate of 2.5 MHz. Each succeeding level of triggering examines fewer events, with more
sophisticated trigger algorithms. At the first stage the Level 1 (L1) system uses a hardware
trigger to reduce the event rate to $\approx$ 5 kHz. At the next stage the Level 2 (L2) system further

reduces the event rate to $\approx$ 1 kHz. L2 uses hardware engines associated with specific detector subsystems and a single global processor for the final L2 trigger decision. In the last step the Level 3 (L3) system which consists of a farm of microprocessors, reduces the event rate to $\approx$ 50 Hz. Only those events that pass all three trigger levels are stored for further offline reconstruction and analysis.

3.4.1   The Level 1 Trigger

The L1 trigger system uses information from the CFT, CPS, FPS, calorimeter and muon subdetectors to provide an event rate reduction by a factor of $\approx$ 500. Field programmable gate arrays (FPGAs) check whether a given event satisfies one of up to 128 L1 trigger conditions. If at least one trigger condition is satisfied the event information is digitized and buffered to await a L2 decision. L1 trigger decisions are made within a 4.2 μs time window.

3.4.1.1   The Level 1 Calorimeter Trigger

For trigger purposes the calorimeter is segmented into 1280 trigger towers of $\Delta\eta \times \Delta\Phi = 0.2 \times 0.2$. Level 1 calorimeter (L1CAL) trigger decisions are based on the amount of transverse energy deposited in the electromagnetic layers (EM) and electromagnetic plus fine hadronic layers (TOT) of the trigger towers. L1CAL trigger conditions require that a specific number of EM or TOT trigger towers be above a certain transverse energy threshold. In addition L1CAL can also impose thresholds on the total sum of transverse energy and the missing transverse energy in a given event.

3.4.1.2   The Level 1 Central Track Trigger

The Level 1 Central Track Trigger (L1CTT) uses information from the CFT and CPS sub-detectors in the central region ($|\eta| <1.7$), and information from the CFT and FPS subdetectors in the forward region ($1.4< |\eta| <2.5$). Possible track candidates are identified by FPGAs using hit patterns in the axial layers of the CFT and matching energy deposits in the preshower detectors (Figure 21). The p_T of a track candidate can be estimated by the azimuthal bend of the CFT hits. L1CTT trigger conditions require that a track candidate be above a certain p_T threshold with the possibility of a matching hit in the corresponding preshower subdetector.

3.4.1.3   The Level 1 Muon Trigger

The Level 1 Muon Trigger (L1Muon) uses information from the muon wire chambers, muon scintillators, and L1CTT tracks. L1Muon trigger logic is implemented in FPGAs and trigger conditions require a combination of criteria based on p_T thresholds, geographical region, track quality and multiplicity.

3.4.2   The Level 2 Trigger

The L2 trigger system was designed to reduce the event rate by a factor of 10. It receives inputs from both the L1 system and the detector subsystems. L2 operates in two stages. In the first stage, subdetector-specific preprocessors form physics objects such as EM energy clusters or tracks. Individual preprocessors for the tracking, preshower, calorimeter and muon subdetectors run in parallel and are located in separate crates. L2 preprocessor physics objects are then used at the second stage by a global processor. The L2 global processor makes the final
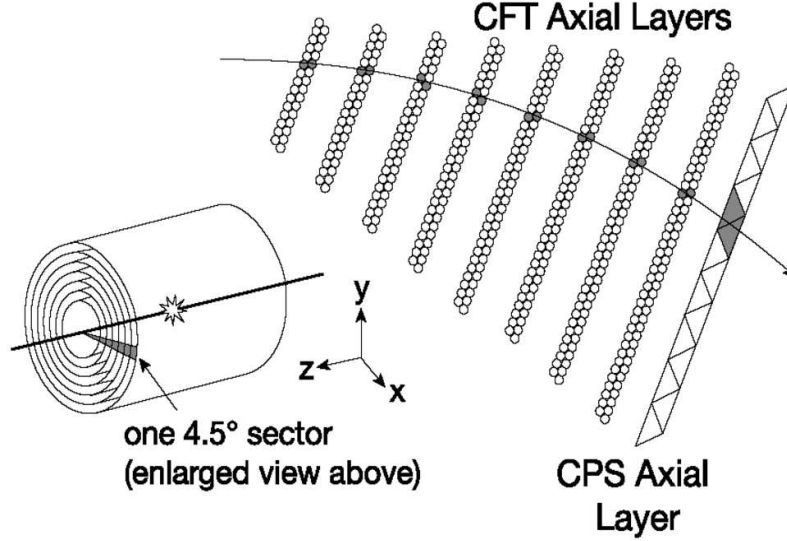
Figure 21. A hypothetical L1CTT track with hits in eight CFT axial doublet layers and the CPS axial layer.

L2 trigger decision by imposing selection criteria on the preprocessor physics object, including correlations between multiple detector subsystems.

The two-stage L2 architecture (*stochastic pipeline*) allows to make trigger decisions within a 100 μs time window (see Appendix B for a detailed description of the L2 trigger system). Events passing L2 trigger requirements are flagged for full detector readout and further refined analysis at the L3 triggering stage.

3.4.2.1   The Level 2 Calorimeter Preprocessor

The Level 2 calorimeter preprocessor (L2Cal) receives the full list of 2560 EM and TOT trigger towers from L1CAL.

The L2 jet algorithm forms jet objects by clustering 5×5 groups of TOT trigger towers centered around seed towers. A jet seed tower is any TOT trigger tower with $E_T \geq 2$ GeV. The list of seed towers for the L2 jet algorithm is E_T-ordered. Depending on the configuration, overlapping L2 jet candidates can be reported as separate jets or simply the highest-E_T jet. An E_T-ordered list of all L2 jets is sent to the L2 global processor.

The L2 Electron/photon algorithm forms EM objects by adding the transverse energies of EM seed towers with their largest E_T neighbors. An EM seed tower is any EM trigger tower with $E_T \geq 1$ GeV. The list of seed towers for the L2 EM algorithm is E_T-ordered. The L2 EM algorithm can be configured in such a way that only the seeds (without considering the neighboring towers) are used to form EM objects. To reduce background the EM energy fractions for both the leading and next-to-leading EM cluster that form the EM object are calculated. Additionally, the isolation of the EM cluster from other energy deposits in the calorimeter is evaluated. An E_T-ordered list of all L2 EM objects and parameters is sent to the L2 global processor.

3.4.2.2   The Level 2 Muon Preprocessors

The Level 2 Muon system (L2Muon) consists of two components: a preprocessor for the central muon region (L2 Muon Central, or L2MUC) and a preprocessor for the forward muon

region (L2 Muon Forward, or L2MUF). L2Muon receives inputs from Level 1 (L1Muon), and the muon subdetector drift chambers and scintillators. This allows to improve muon triggering capabilities by incorporating better calibration and timing information from the muon scintillators. Muon tracks at L2 contain η and ϕ information, as well as p_T, sign, and timing information.

3.4.2.3   The Level 2 Preshower Preprocessor

The Level 2 preshower preprocessor (L2PS) receives inputs from the L1 trigger system. Based on preshower detector information it forms clusters with η and ϕ coordinates that can then be matched with calorimeter trigger towers or CFT trigger tracks at the L2 global processing stage.

3.4.2.4   The Level 2 Tracking Preprocessor

The Level 2 tracking preprocessor uses information from L1CTT and the SMT to form lists of L2 track candidates that can be used by the L2 global processor for triggering. This part of the L2 trigger system is still under development. It would allow to trigger on vertices that are displaced from the primary interaction vertex. Displaced vertices are characteristic of long-lived particles such as B-Mesons, and can therefore be used to identify heavy-flavored quarks.

The L2 tracking preprocessor can be operated in two different modes. In the first mode of operation (L2 Central Track Trigger, or L2CTT) it further refines tracking information coming from L1CTT. In the second mode of operation (L2 Silicon Track Trigger, or L2STT) it combines L1CTT and SMT information. Figure Figure 22 shows the conceptual design of L2STT. It uses hit information from the first and last layer of the CFT to define a *road*, and then extrapolates
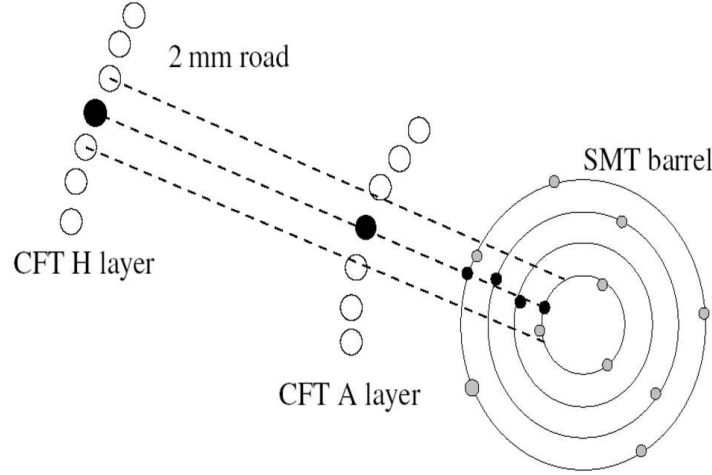
Figure 22. The definition of roads based on L1 tracks and SMT hit selection in L2STT.

that road into the SMT to find additional hits in the axial strips of the SMT silicon ladders.

3.4.2.5   The Level 2 Global Processor

The Level 2 global processor (L2GBL) receives lists of trigger objects that are generated by the L2 preprocessors (L2Cal, L2MUC, L2MUF, L2PS, L2CTT, L2STT). It creates global trigger objects by either using the trigger objects generated by the preprocessors or by combining trigger object information from different preprocessors. For example, spacial correlations between track candidates and EM energy deposits in the calorimeter can be used to select electron candidates. L2GBL makes the final L2 trigger decision by imposing cuts on global trigger objects that are defined by trigger list information which is parsed from the trigger control computer.

3.4.3   The Level 3 Trigger and Data Acquisition

Both the L1 and L2 trigger systems do not use the full detector readout for their trigger decisions. The event rate needs to be reduced to 1 kHz or below, so that the Level 3 (L3) trigger system can take advantage of the full detector readout. L3 then further reduces the event rate to 50 Hz. The average event size is ≈ 300 kByte.

The L3 trigger system is based on software algorithms that resemble the algorithms for offline event reconstruction (see Chapter 4) as closely as possible, given restrictions due to available processing power.

The data acquisition system (L3DAQ) is based on a single Cisco 6509 Ethernet switch that allows data transfer rates of 250 Mbyte/s. Figure 23 illustrates the main hardware components of the data acquisition system. Detector data is transfered from commodity VME single-board computers (SBCs), via the Ethernet switch to the individual L3 farm nodes. A supervisor process running on a separate CPU provides the interface between the main DØ run control system (COOR) and L3DAQ.

After passing L3 trigger requirements the data are transferred to a permanent storage facility.
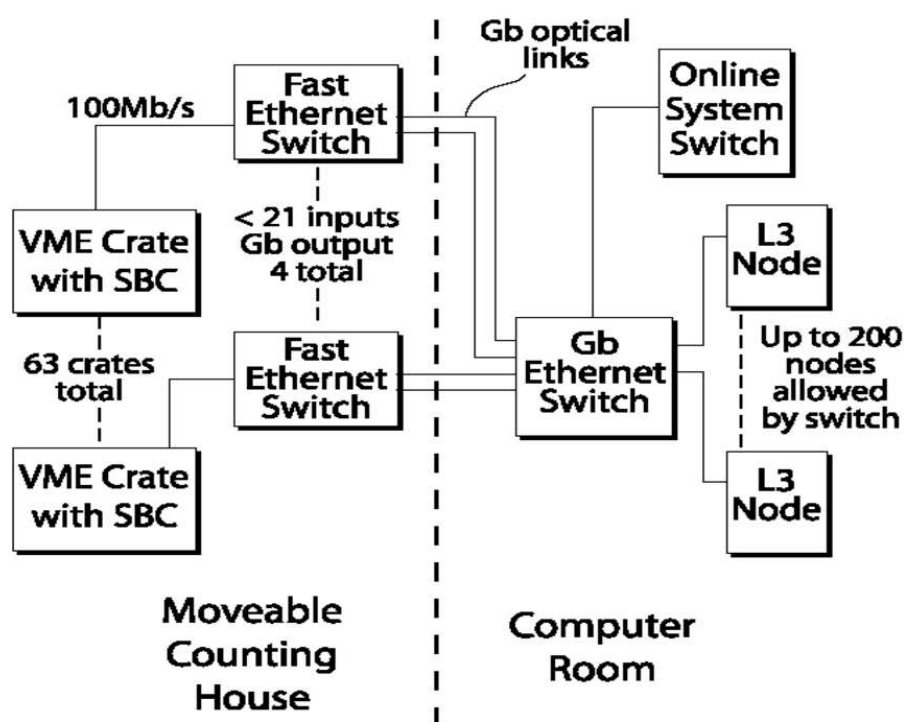
Figure 23. Main L3DAQ hardware components.

CHAPTER 4

OFFLINE EVENT RECONSTRUCTION

This chapter describes how physical objects like electrons or jets, are formed or *reconstructed* from the raw detector data. A collection of complex software algorithms written in C++ called *d0reco* (27) is used for this reconstruction process. As described in the previous chapter a stream of digital readout signals from the subdetectors is being recorded for each event that passes all three levels of triggering. Powerful PC computing farms are deployed to analyze the data and reconstruct candidates of physical objects (electrons, jets, tracks, etc) that can then be used in the final analysis.

4.1   Track Reconstruction

In order to reconstruct track candidates, two different types of algorithms are used. The *Alternative Algorithm* (AA) (28) uses a road-following method, while the *Histogramming Track Finder* (HTF) (29) relies on a histogramming method.

The AA method starts from any combination of three hits in SMT barrels or disks. Moving outwards, towards the CFT, it then extrapolates the sequence of hits to the next SMT or CFT layer. If a hit is found within a configurable expectation window a χ^2 test is performed. If the χ^2 value is below a configurable threshold, the newly found hit is associated with the track candidate. If no hit is found, it is recorded as a *miss*. Construction of track candidates ends until the last layer of the CFT is reached, or until three misses are recorded.

The HTF method takes advantage of the fact that the trajectory of a charged particle moving perpendicular to a homogeneous magnetic field can be characterized by the three parameters ρ, d_0, Φ; where $\rho = qB/p_T$ is the radius of curvature, d_0 is the distance of closest approach with respect to (0,0) (*impact parameter*), and Φ is the direction of the track at the point of closest approach to (0,0). Examining only track candidates with small impact parameters, every pair of hits in (x,y) coordinate space belonging to the same track, corresponds to a single point in parameter space (ρ, Φ). Therefore, after examining every pair of hits and filling a 2-D (ρ, Φ) histogram, a peak in the histogram corresponds to a track candidate.

Both algorithms generate lists of track candidates that are combined after removing duplicates, and applying additional selection criteria based on number of hits, number of misses, and χ^2 value. Figure 24 shows an example of hits and reconstructed tracks (30).

4.2   Primary Vertex Reconstruction

The primary vertex (PV) is the location of the proton-antiproton hard scatter collision. It is important to identify the position of the PV with high accuracy, since it is an essential ingredient to reconstruct jets, electrons and missing transverse energy. It is also important to select an algorithm (31) that allows to distinguish between the hard scatter vertex and vertices from additional *minimum bias* (MB) interactions.

Based on the list of reconstructed tracks (see Chapter 4.1) a list of vertices is generated by extrapolating the tracks back to the z-axis. Clusters of vertices are then formed by selecting vertices within 2 cm of each other along the z-axis. In each vertex cluster, the vertex with the highest number of tracks pointing at it, is stored in a list of "selected" vertices. For every se-
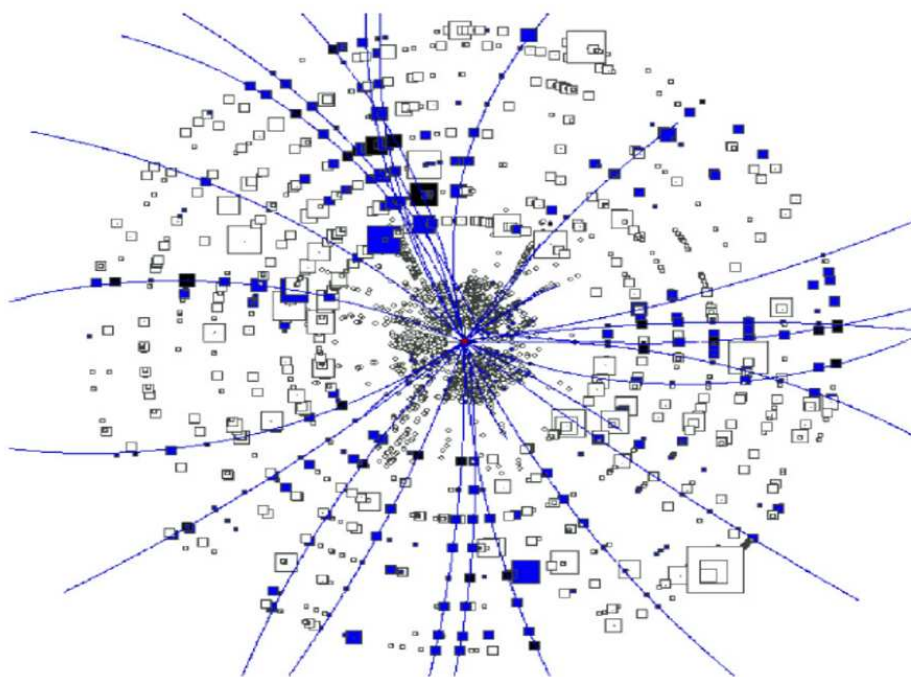
Figure 24. Axial view (looking down the beam-pipe) of a recorded event showing hits and reconstructed tracks. CFT hits are represented by squares, and SMT hits are represented by circles. Hits are colored solid if they are associated with a reconstructed track (solid lines). The curvature of the reconstructed tracks is due to the solenoidal magnetic field, which is pointing out of the page.

lected vertex, tracks nearby are used to compute the probability that the vertex does not come from a MB interaction. The computation of this probability is based on the assumption that tracks coming from MB interactions will have a smaller transverse momentum, as tracks coming from the hard scatter. Finally, the vertex with the smallest MB probability is chosen as the PV.

4.3   Electromagnetic Object Reconstruction and Identification

Electromagnetic objects (EM objects), such as electrons and photons, are initially identified based on calorimeter information. Since photons are not generating any signals in the tracking system, requiring a track that matches the energy deposit in the calorimeter allows to distinguish electrons from photons.

EM object reconstruction starts by forming initial calorimeter clusters. Different algorithms can be used to find those initial clusters:

- Simple-Cone tower clustering algorithm ("Scone Method")

- Cell Nearest Neighbor clustering algorithm ("CellNN Method")

- Track extrapolation clustering algorithm ("Road Method")

In this analysis, objects reconstructed with the simple cone algorithm are used.

4.3.1   Simple-Cone Clustering Algorithm

The simple-cone algorithm (32) clusters calorimeter cells of size $\Delta\eta \times \Delta\Phi = 0.1 \times 0.1$. Each cell is required to have at least 1.5 GeV of transverse energy. Additionally, for each cell the
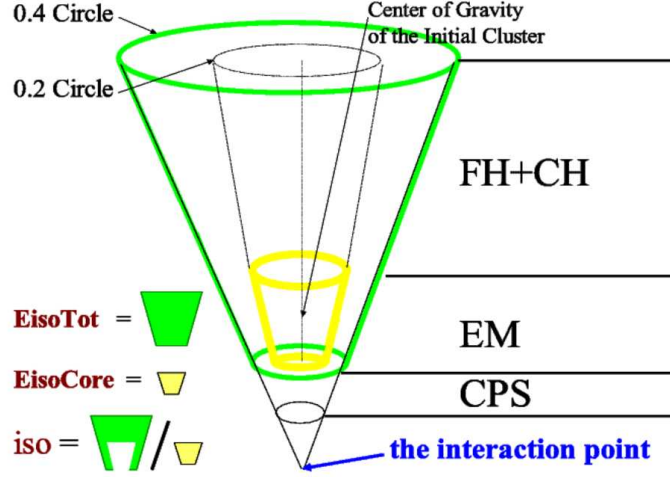
Figure 25. Illustration of the Isolation Parameter: *EisoTot* is the total energy in a cone of radius 0.4, and *EisoCore* is the energy in the EM layers in a cone of radius 0.2.

ratio of the energy in the EM layers to the total energy (EM fraction) is required to be above 0.9. Next, all clusters satisfying the above criteria are tested for *isolation*:

$$isolation = \frac{EisoTot - EisoCore}{EisoCore} \tag{4.1}$$

Figure 25 illustrates the definition of the isolation parameter (32). All initial EM clusters are required to have an isolation of less than 0.2. The isolation parameter gives a measure of how deep and narrow a given cluster is. EM objects tend to deposit most of their energy in a narrow region of the EM layers, while hadrons deposit their energies in the hadronic layers in a much wider radius.

4.3.2   Electromagnetic Object Identification Parameters

A set of various parameters is calculated for every EM cluster that passes the initial quality criteria. This allows flexibility when defining EM objects at the analysis stage.

ID: All EM clusters that pass the initial quality criteria are assigned an ID of 10. If in addition a cluster has a track loosely matched to it, it is assigned an ID of ± 11 ("+" for electrons, "−" for positrons).

Isolation: See Chapter 4.3.1.

Electromagnetic Fraction: The electromagnetic fraction (EM fraction) is another discriminant between EM and hadronic calorimeter energy deposits. It takes advantage of the fact that EM showers are almost entirely contained within the EM layers of the calorimeters. Figure 26 illustrates the definition of the EM fraction parameter (32).

H-Matrix: The H-Matrix technique allows a distinction between EM and hadronic energy deposits, by analyzing the longitudinal and transverse shape of the showers. Based on MC generated electrons a covariance matrix (M) is defined using a set of seven discriminant variables :

$$M_{ij} = \frac{1}{N} \sum_{n=1}^{N} \left(x_i^n - \langle\ x_i\ \rangle \right) \left(x_j^n - \langle\ x_j\ \rangle \right) \tag{4.2}$$

where x_i^n is the value of variable i for electron n, and $\langle\ x_i\ \rangle$ is the mean value of variable i. The seven variables that are used are listed below:

- Shower energy fraction in 1st, 2nd, 3rd, and 4th EM layer of the calorimeter.

- Cluster size in $r\Phi$ based on the 3rd EM layer of the calorimeter.
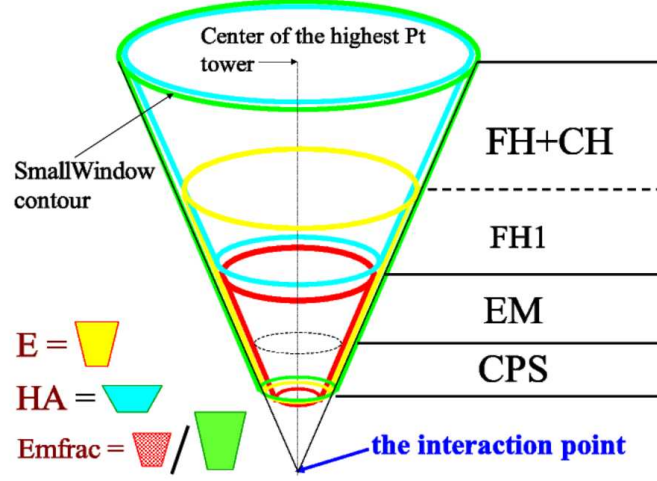
Figure 26. Illustration of the EM fraction parameter: EM fraction is the ratio between the energy in the CPS plus EM layers, and the energy in the CPS plus EM layers plus hadronic layers.

- Total shower energy.

- Primary vertex position.

The H matrix is defined as the inverse of the covariance matrix (Equation 4.2):

$$H \equiv M^{-1} \tag{4.3}$$

Using the H matrix one can calculate a χ^2-like variable that gives a measure of the likelihood that a given shower k is consistent with an EM object shower:

$$\chi^2 = \sum_{ij} (x_i^k - \langle x_i \rangle) H_{ij} (x_j^k - \langle x_j \rangle) \tag{4.4}$$

Track Matching: Requiring that a track is associated with a calorimeter EM cluster allows to distinguish electrons from photons. In this analysis *global tracks* are used for tracking confirmation, i.e. tracks based on information from both the CFT and SMT subdetectors. Using calorimeter and tracking information the following χ^2 variable is calculated:

$$\chi^2 = \left(\frac{\Delta\Phi}{\sigma_\Phi}\right)^2 + \left(\frac{\Delta z}{\sigma_z}\right)^2 + \left(\frac{E_T/p_T - 1}{\sigma_{E/p}}\right)^2 \tag{4.5}$$

where in Equation 4.5:

- $\Delta\Phi$ (Δz) is the difference in Φ (z) between the EM cluster position in the 3rd EM calorimeter layer and the extrapolation of the track to the same layer.

- σ_Φ, σ_z, and $\sigma_{E/p}$ are the root-mean-squares of the experimental measurements of each quantity.

- E_T/p_T is the ratio of the transverse energy of the EM calorimeter cluster and the transverse momentum of the track.

A track is matched to an EM cluster by requiring that the track matching χ^2 probability is $P(\chi^2) > 10^{-2}$.

4.4   <u>Jet Reconstruction and Identification</u>

Individual quarks and gluons cannot be detected directly due to color confinement. Instead, collimated streams of hadrons (*jets*) are observed in the detector. In this chapter we discuss the techniques that are used to reconstruct and identify jets.

4.4.1   <u>Jet Cone Algorithm</u>

The general idea behind a jet cone algorithm is to define cones in $\eta \times \Phi$ space that contain the energy of a jet that is associated with a certain parton which emerged from the interaction region. The following describes the jet cone algorithm that was used to reconstruct the jets that were used in this analysis (33):

1. Jet reconstruction is based on the total transverse energy (E_T) of calorimeter towers ($\Delta \eta \times \Delta \Phi = 0.1 \times 0.1$). Only towers with $E_T > 0.5$ GeV are considered.

2. Starting with the highest E_T tower as a seed, *preclusters* are formed by adding the transverse energies of all towers within a radius of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \Phi)^2} = 0.3$ around the seed towers. Only preclusters with $E_T > 1.0$ GeV are considered. Towers cannot be shared amongst different preclusters.

3. For every precluster the E_T (Equation 4.6) and E_T weighted cone centroid (Equation 4.7, Equation 4.8) are calculated:

$$E_T \equiv \sum_i E_T^i = \sum_i E_i \times \sin \theta_i \tag{4.6}$$

$$\eta = \frac{\sum_i E_T^i \, \eta_i}{\sum_i E_T^i} \tag{4.7}$$

$$\Phi = \frac{\sum_i E_T^i \ \Phi_i}{\sum_i E_T^i} \tag{4.8}$$

4. The E_T in a cone of radius $\Delta R = 0.5$ around each precluster is calculated, as well as the cone axis. This step is repeated until the cone axis becomes stable. Each stable cone is added to a list of *proto-jets*. Only proto-jets with $E_T > 8.0$ GeV are considered.

5. Using a similar clustering procedure as before, midpoints between any combination of two proto-jets are also used as seeds and iterated until stable cones are found. This step is done to remove sensitivity to soft radiation.

6. After receiving a list of proto-jets coming from preclusters and midpoints, the proto-jets are checked for overlapping regions. In order to avoid double counting of energy a merging/splitting algorithm is applied. Two proto-jets are *merged* if the shared energy between them is greater than half of the lower E_T proto-jet. Otherwise, the two proto-jets are *split* and the tower energies are assigned to the closest proto-jet.

4.4.2 Jet Identification Parameters

A set of quality cuts is applied to every reconstructed jet, in order to reduce fake jets from calorimeter noise.

EM Fraction (EMF): Hadronic shower formation tends to distribute energy evenly in the EM and hadronic layers of the calorimeter, whereas EM objects mostly shower in the EM layers. Therefore, a cut on the fraction of transverse energy in the EM layers allows to distinguish jets from EM objects.

Coarse Hadronic Fraction (CHF): Coarse hadronic fraction is the fraction of transverse energy of a jet jet that is deposited in the coarse hadronic layers of the calorimeter.

Hot Fraction (HotF): Hot Fraction is the ratio of transverse energy in the most energetic tower to that of the next most energetic tower in the jet. If a significant amount of the total jet energy is originating from a single calorimeter tower, it is likely that the tower is generating artificially high read-out signals due to detector problems (*hot tower*). A cut on the Hot Fraction parameter allows to eliminate jets originating from hot towers.

N90: N90 is the number of towers making up 90% of the jet energy. A cut on the N90 parameter allows to eliminate jets originating from hot towers as well.

L1 Confirmation: L1 confirmation was introduced in order to deal with calorimeter cell precision readout noise. The parameter compares the jet energy at the L1 trigger tower level with the jet energy derived from the jet cone algorithm, which is based on calorimeter cell precision readout:

$$L1conf = \frac{\sum_{trigger} E_T^i}{E_T^{jet} \cdot (1 - CHF)} \tag{4.9}$$

where $\sum_{trigger} E_T^i$ is the sum of transverse TOT trigger tower energies within $\Delta R < 0.5$ of the reconstructed jet; E_T^{jet} is the transverse energy of the reconstructed jet; and CHF is the Coarse Hadronic Fraction of the reconstructed jet.

4.4.3 Jet Energy Scale

The jet energy scale (JES) is a calibration that adjusts the measured jet energy for various effects (34). Depending on the jet E_T and jet η it applies a calibration factor that allows to

obtain the particle level jet E_T ($E_{jet}^{particle}$) from the measured jet E_T ($E_{jet}^{calorimeter}$) according to the following relation:

$$E_{jet}^{particle} = \frac{E_{jet}^{calorimeter} - E_{offset}}{R_{jet} \cdot R_{cone}} \tag{4.10}$$

where E_{offset} is the *offset energy*, R_{jet} is the *jet response* correction, and R_{cone} is the *out of cone showering* correction.

Offset Energy: Any energy contributions to the jet reconstruction that are not related to the physics processes that are responsible for creating a jet need to be subtracted from the measured jet energy. The offset energy term contain contributions from multiple interactions, underlying event energy, electronic noise, uranium noise, and pile-up from previous bunch crossings.

Jet Response: The jet response correction takes into account the calorimeter response to the hadronic jets, i.e. the amount of energy that is lost due to uninstrumented regions and dead material in the calorimeter. The correction is estimated from the p_T imbalance in back-to-back photon+jet events. Since photon E_T can be measured to a high level of accuracy, this allows a good estimation of the jet response.

Out of Cone Showering: Due to interactions between the particles that comprise a jet and detector material, it is possible that some particles produced inside (outside) the jet algorithm cone deposit a fraction of their energy outside (inside) of the cone. Additionally, particle trajectories can get bent in the magnetic field, which again can lead to energy being deposited inside or outside of the jet cone.
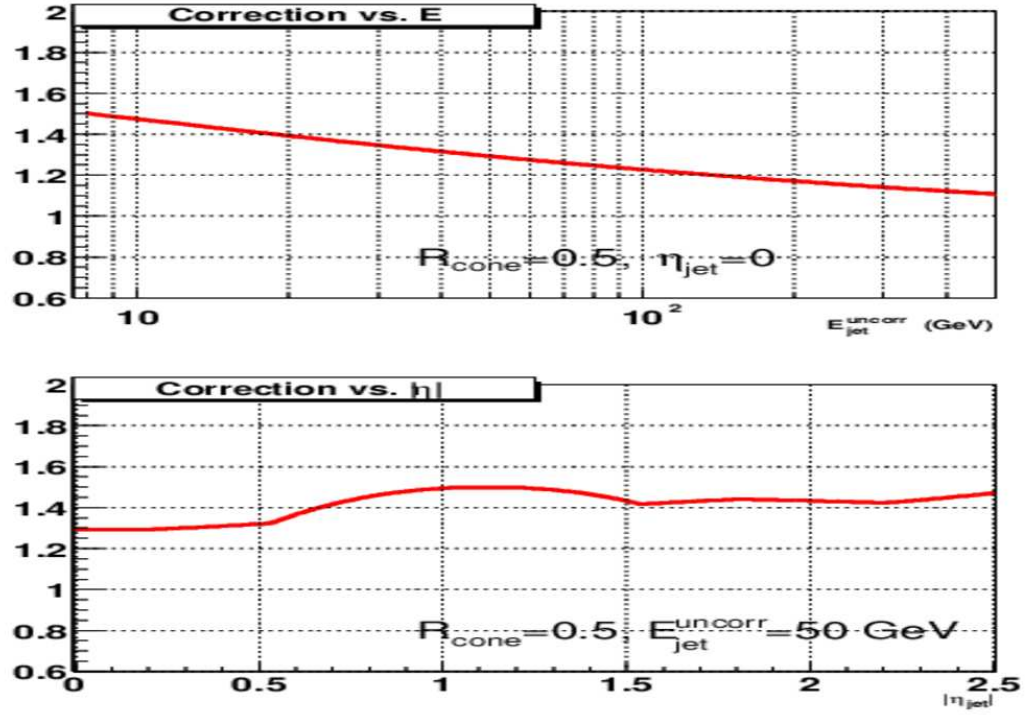
Figure 27. The jet energy scale correction factor measured for jets in data as a function of E (top) and η (bottom).

Figure 27 shows the overall jet energy scale corrections as a function of E and η (35).

CHAPTER 5

DATA AND MONTE CARLO SAMPLES

5.1   <u>Data Sample</u>

5.2   <u>Monte Carlo Samples</u>

CHAPTER 6

ANALYSIS

6.1   Samples

6.1.1   Data Sample

The dataset used for this analysis was collected between April 2002 (Run 151,817) and June 2004 (Run 194,566) and contains approximately 1 billion events. The raw data were converted into thumbnails using the p14 version of the DØ reconstruction software and then further skimmed using EM1TRK skim criteria: requiring at least one EM object with ID = 10 or ± 11 and $p_T > 8$ GeV, and a TRK object with $p_T > 5$ GeV within $\Delta\phi = 0.1$ of the EM object. Approximately 57 million events met these preselection criteria. ATHENA (36) p16-br-03 with JES 5.3 was used to produce the root-tuples and T42 (37) corrections were applied (Pass 2 data). These root-tuples were then further skimmed by requiring at least one EM object with EM Fraction > 0.9, Isolation< 0.15, H-Matrix(7)< 12.0, $|\eta_{det}| < 1.1$ and a track match[1] in each event. The final analysis root-tuple contains 2.4 million events.

Using the run quality database, runs for which the SMT, CFT and Calorimeter subsystems were flagged as "bad" were excluded from the analysis (using run numbers) - events that were flagged as "bad" by the CalJetMet group or the luminosity system were excluded as well (using LBNs). Additionally all runs with limited L1CAL trigger coverage ($|\eta| < 0.8$) were excluded

---

[1]χ^2 probability for best track using the distance in η/Φ and E/p

(38).

Events were selected based on a combination of unprescaled single electron triggers. The following is the prioritized order of trigger combinations for trigger lists before global_CMT-12 (runs $\leq$ 178732, "pre-v12 dataset")[1] (39):

- EM_HI_SH or EM_HI_2EM5_SH

- EM_HI_SH

- EM_HI

- EM_MX_SH

- EM_MX

The Level 2 trigger subsystem was not available for the entire pre-v12 dataset (all runs with run numbers $\leq$ 169,523) in which case we do not require the Level 2 trigger condition to be satisfied.

The trigger combinations for trigger list global_CMT-12 (runs $\geq$ 178722, "v12 dataset") are:

- E1_SHT20 or E2_SHT20 or E3_SHT20 or E1_SH30

- E1_SHT20 or E2_SHT20 or E1_SH30

- E1_SHT20 or E1_SH30

---

[1] "Trigger A or Trigger B" = if Trigger A and Trigger B are unprescaled, accept the event if Trigger A or Trigger B fired

- E1_SHT20

Table I contains details of the individual triggers.

A total integrated luminosity of 343 pb^{-1} was available for this analysis after trigger selection and bad run/LBN rejection.

6.1.2 <u>Monte Carlo Samples</u>

The MC samples used for this analysis are summarized in Table II. For studies regarding the inclusive $Z/\gamma^* \to e^+e^-$ cross section a PYTHIA (40) $Z/\gamma^* \to e^+e^-$ inclusive sample was used. For higher jet multiplicities, events were generated with ALPGEN (41) and then passed through PYTHIA for parton showering and hadronization. Since the electron energy resolution in data is not correctly described by the MC simulation, additional energy smearing is applied to the MC electrons. The p_T (as well as p_x, p_y, p_z and Energy) of the electrons is replaced by $p_T \to p_T \cdot c \cdot \text{Gauss}(1, f)$ where Gauss(1,f) is the smearing parameter which is randomly chosen from a Gaussian distribution with mean 1 and width f. c is an overall calibration factor. For this analysis the following values were used (42):

- f = 0.045

- c = 1.003

TABLE I

SINGLE EM TRIGGERS USED IN THIS ANALYSIS

Trigger	L1	L2	L3
EM_HI_SH	CEM(1,10)	EM(1,12)	ELE_LOOSE_SH_T(1,20)
EM_HI_2EM5_SH	CEM(2,5)	EM(1,12)	ELE_LOOSE_SH_T(1,20)
EM_HI	CEM(1,10)	EM(1,12)	ELE_LOOSE(1,30)
EM_MX_SH	CEM(1,15)	none	ELE_LOOSE_SH_T(1,20)
EM_MX	CEM(1,15)	none	ELE_LOOSE(1,30)
E1_SHT20	CEM(1,11)	none	ELE_NLV_SHT(1,20)
E2_SHT20	CEM(2,6)	none	ELE_NLV_SHT(1,20)
E3_SHT20	CEM(1,9)CEM(2,3)	none	ELE_NLV_SHT(1,20)
E1_SH30	CEM(1,11)	none	ELE_NLV_SH(1,30)

L1 Triggers	
CEM(1,10)	one EM trigger tower with $E_T > 10$ GeV
CEM(2,5)	two EM trigger towers with $E_T > 5$ GeV
CEM(1,15)	one EM trigger tower with $E_T > 15$ GeV
CEM(1,11)	one EM trigger tower with $E_T > 11$ GeV
CEM(2,6)	two EM trigger towers with $E_T > 6$ GeV
CEM(1,9)CEM(2,3)	one EM trigger tower with $E_T > 9$ GeV, another EM trigger tower with $E_T > 3$ GeV

L2 Triggers	
EM(1,12)	one EM candidate with $E_T > 12$ GeV (not present for runs below 169524)

L3 Triggers	
ELE_LOOSE_SH_T(1,20)	one electron with $|\eta| < 3.0$ and $E_T > 20$ GeV passing loose requirements including shower shape cuts
ELE_LOOSE(1,30)	one electron with $|\eta| < 3.0$ and $E_T > 30$ GeV passing loose requirements
ELE_NLV_SHT(1,20)	one electron with $|\eta| < 3.6$ and $E_T > 20$ GeV passing tight shower shape cuts
ELE_NLV_SH(1,30)	one electron with $|\eta| < 3.6$ and $E_T > 30$ GeV passing loose shower shape cuts

We also apply jet resolution smearing to the MC jets based on the jet resolution in data and MC derived with JES 5.0 (with T42)(43). Equation Equation 6.1 shows the resolution parameterization where N, S and C denote the noise, sampling and constant terms (respectively).

$$\frac{\sigma(p_T)}{p_T} = \sqrt{\frac{N^2}{p_T^2} + \frac{S^2}{p_T} + C^2} \tag{6.1}$$

Table III summarizes all coefficients for different detector regions.

Using the p_T and η_{det} of the MC jets, we calculate the data and MC resolutions. If for a given jet the data resolution is better than the MC resolution, we do not apply any additional smearing. If the resolution is worse in data than in MC, we calculate a multiplicative smearing factor (Equation 6.2) and apply it to the p_T of the jet.

$$\text{Smearing Factor} = \text{Gauss}\left(1, \sqrt{\left(\frac{\sigma(p_T)}{p_T}\right)^2_{data} - \left(\frac{\sigma(p_T)}{p_T}\right)^2_{MC}}\right) \tag{6.2}$$

Process	Generators	SAM Dataset definition	Size
$Z(\gamma^*) \to e^+e^-$	PYTHIA (CTEQ5 PDF)	p14.05.01_pythia_zee_m60-130	400k
$Zj \to e^+e^-j$	ALPGEN + PYTHIA	p14.05.01_alpgen_pythia_zj_eej	150k
$Zjj \to e^+e^-jj$	ALPGEN + PYTHIA	pdt-zjj-eejj-p14tmb	180k
$Zjjj \to e^+e^-jjj$	ALPGEN + PYTHIA	p14.07.00_alpgen_pythia_zjjj_eejjj	15k

TABLE II

LIST OF MC SAMPLES

Coefficient	$|\eta_{det}| < 0.5$	$0.5 < |\eta_{det}| < 1.0$	$1.0 < |\eta_{det}| < 1.5$	$|\eta_{det}| > 1.5$
N_{data}	5.05	$9.06 \cdot 10^{-9}$	2.24	6.42
S_{data}	0.753	1.2	0.924	$4.5 \cdot 10^{-10}$
C_{data}	0.0893	0.087	0.135	0.0974
N_{MC}	4.26	4.61	3.08	4.83
S_{MC}	0.658	0.621	0.816	$5.13 \cdot 10^{-7}$
C_{MC}	0.0436	0.0578	0.0729	0.0735

TABLE III

JET RESOLUTION PARAMETERS IN DATA AND MC.

6.2   Event Selection

6.2.1   Primary Vertex

The primary vertex is required to be within 60 cm of the detector center along the beam pipe (z-axis).

6.2.2   Electron Selection

Electromagnetic objects have to satisfy the following requirements:

- Loose electrons:

  - ID = 10 or ± 11

  - EM Fraction > 0.9

  - Isolation < 0.15

  - H-Matrix(7) < 12

  - $p_T > 25$ GeV

- $|\eta_{det}| < 1.1$

- No fiducial restrictions in ϕ

- Tight electrons:

  - Requirements of loose electron.

  - Track match[1] with $P(\chi^2) > 0.01$

6.2.3 $\underline{Z \text{ Selection}}$

Z bosons are selected based on the following criteria:

- Two loose electrons.

- At least one of the two electrons needs to be tight.

- At least one of the two electrons needs to have matching trigger objects at L1, L2 and L3 for one of the unprescaled single electron triggers that fired in a given event. The trigger objects also need to satisfy the trigger requirements for those triggers.

- 75 GeV $< M_{ee} < 105$ GeV

6.2.4 $\underline{\text{Jet Selection}}$

Jets are formed using a simple cone jet algorithm with a cone size of 0.5 and are selected based on the following criteria:

- $0.05 < \text{EMF} < 0.95$

---

[1]χ^2 probability for best track using the distance in η/Φ and E/p

- HotF < 10.

- N90 > 1.

- CHF < 0.4

- L1 confirmation

- JES corrected $p_T > 20$ GeV

- $|\eta_{physics}| < 2.5$

- Removal of all jets overlapping with electrons coming from the Z boson within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of 0.4

6.2.5 Event Statistics

Table IV gives an overview of the event statistics with regard to exclusive jet multiplicities.

6.3 Data vs Monte Carlo

6.3.1 Primary Vertex Comparison

Figure 28 compares the primary vertex distribution between data and inclusive $Z/\gamma^* \rightarrow e^+e^-$ PYTHIA MC.

6.3.2 Z p_T Comparisons

Figure 29 shows the Z p_T comparison between data and PYTHIA. Since PYTHIA does not fully incorporate higher-order contributions of hard radiation to the Drell-Yan process, there is a disagreement on the Z p_T distribution (especially at high p_T) with the data. To account
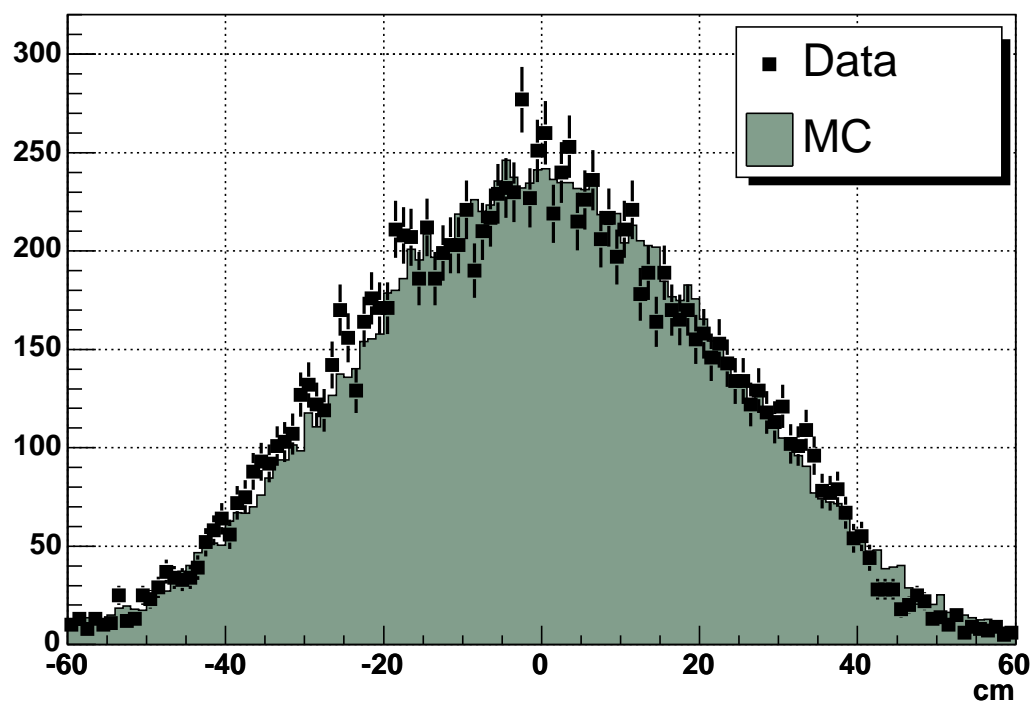
Figure 28. Primary vertex distribution in data and MC (PYTHIA) for the inclusive sample.

Sample	N	Fraction
$Z/\gamma^* + 0$ jets	12,247	0.8815
$Z/\gamma^* + 1$ jets	1,427	0.1027
$Z/\gamma^* + 2$ jets	189	0.0136
$Z/\gamma^* + 3$ jets	25	0.0018
$Z/\gamma^* + 4$ jets	3	0.0002
$Z/\gamma^* + 5$ jets	2	0.0001
Total	13,893	1.0000

TABLE IV

EVENT BREAKDOWN BY EXCLUSIVE JET MULTIPLICITIES ASSOCIATED WITH Z/γ^* PRODUCTION BEFORE ANY BACKGROUND IS SUBTRACTED OR ANY CORRECTION IS APPLIED.

for this discrepancy, an additional correction based on the Z p_T comparison between data and MC is applied. The Z p_T correction is also shown in Figure 29.

Figure 30 and Figure 31 show Z p_T comparisons when using ALPGEN + PYTHIA for $Z+1$ jet and $Z+2$ jet samples. We do not apply an additional Z p_T correction when using the ALPGEN MC samples.

6.3.3 $Z/\gamma^* \to e^+e^- + \geq n$ Jet Comparisons

6.3.3.1 $Z/\gamma^* \to e^+e^-$ Inclusive Sample

We compare basic kinematic distributions for electrons and Z candidates after applying all corrections (Trigger, EM, Tracking, Z p_T - see Chapters 6.4.1 and 6.5.1 for a description of the corrections). All distributions are normalized by area. Figure 32 compares basic electron
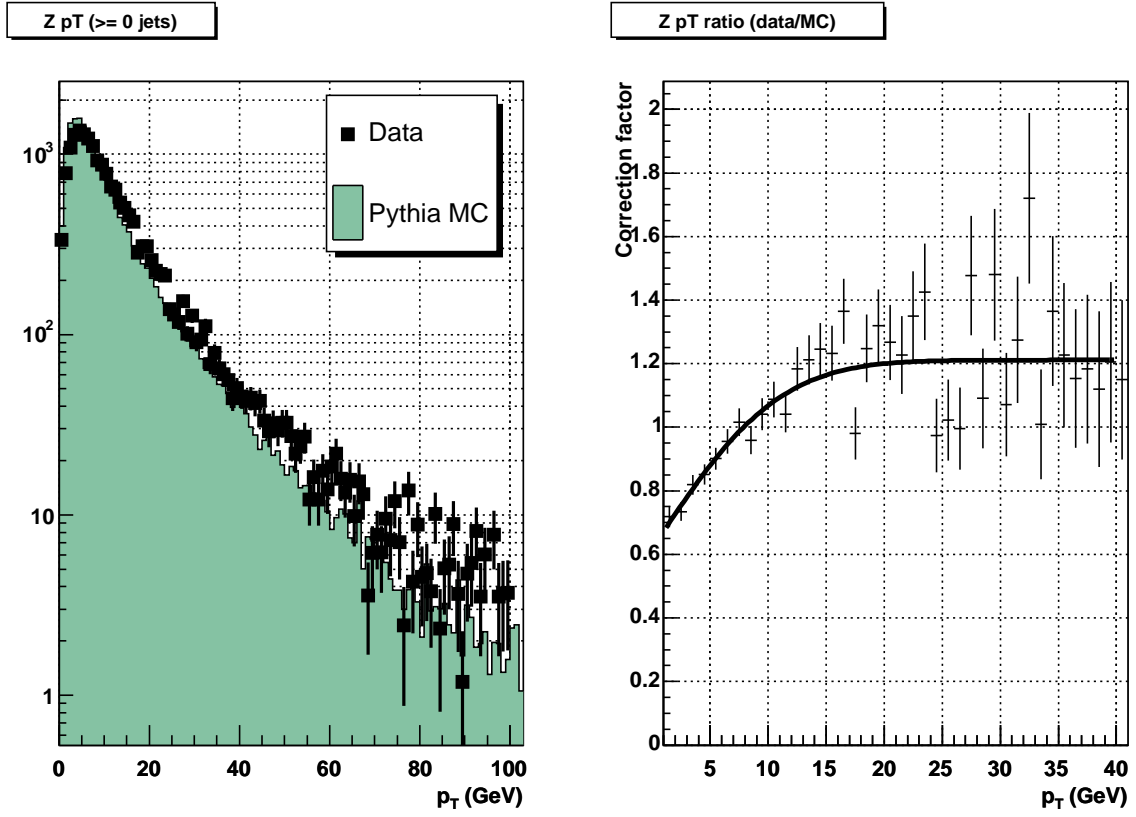
Figure 29. Comparing Z p_T between data and PYTHIA MC (left), and ratio correction factor (right).
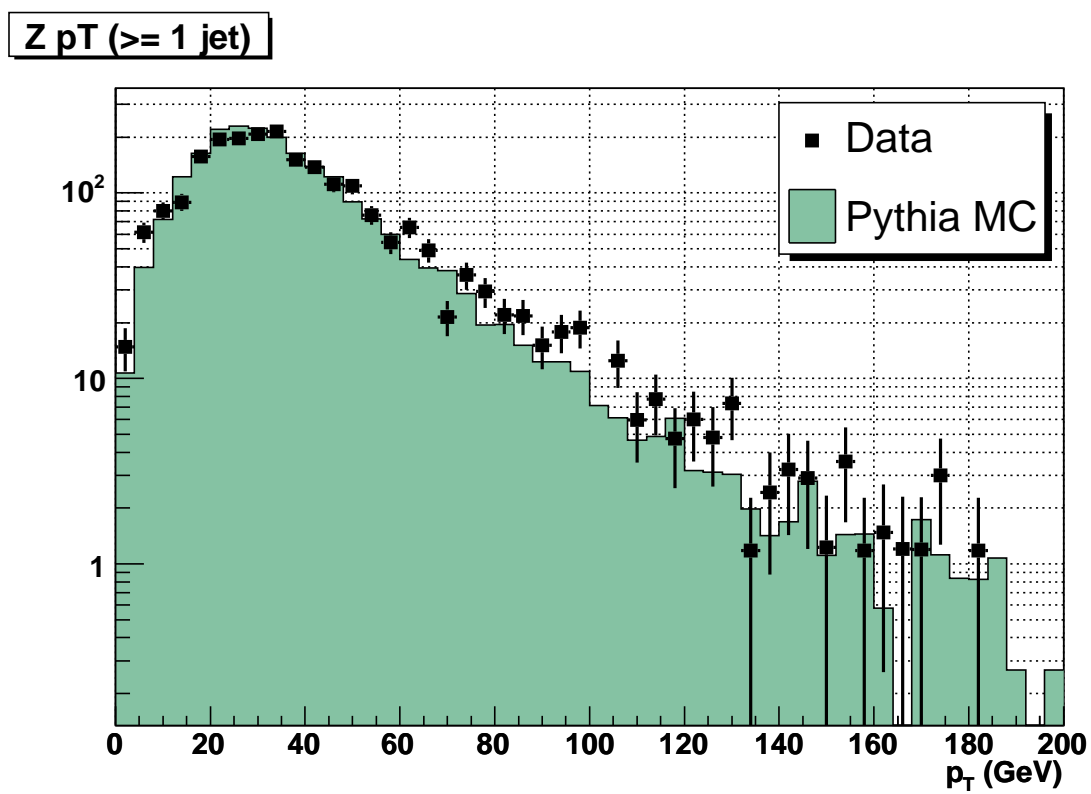
Figure 30. Comparing Z p_T between data and ALPGEN + PYTHIA $Z+1$ jet MC.

Z pT (>= 2 jets)
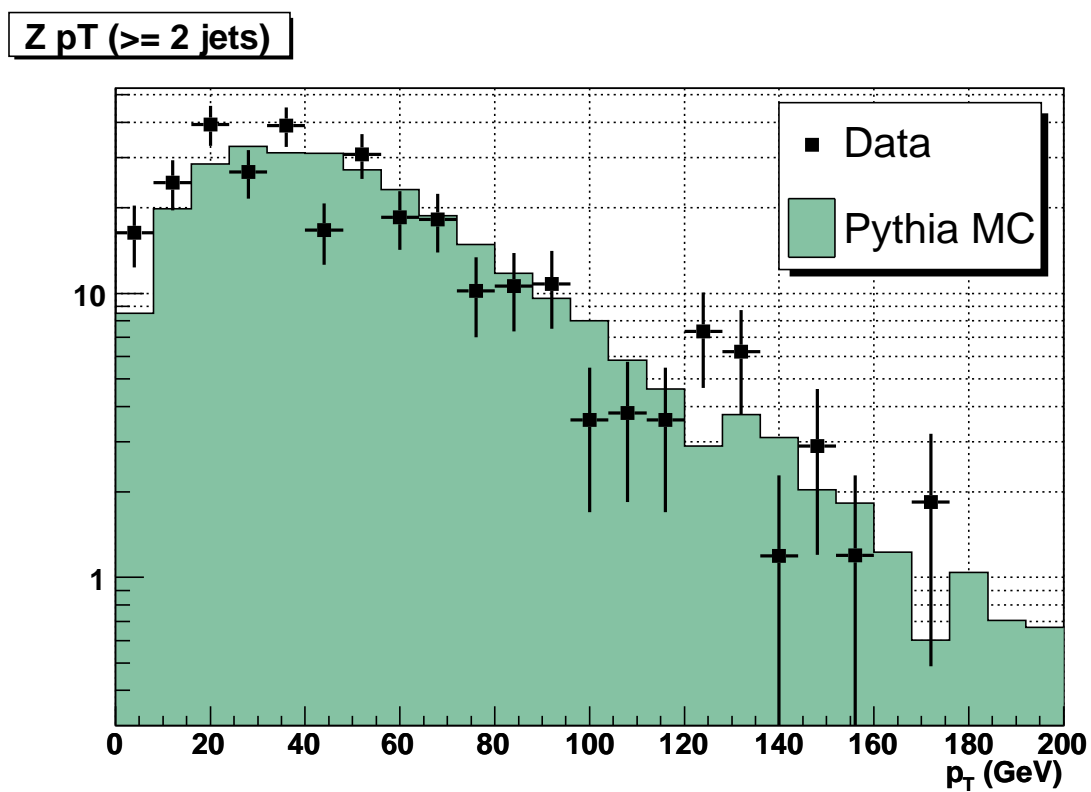
Figure 31. Comparing Z p_T between data and ALPGEN + PYTHIA $Z+2$ jets MC.
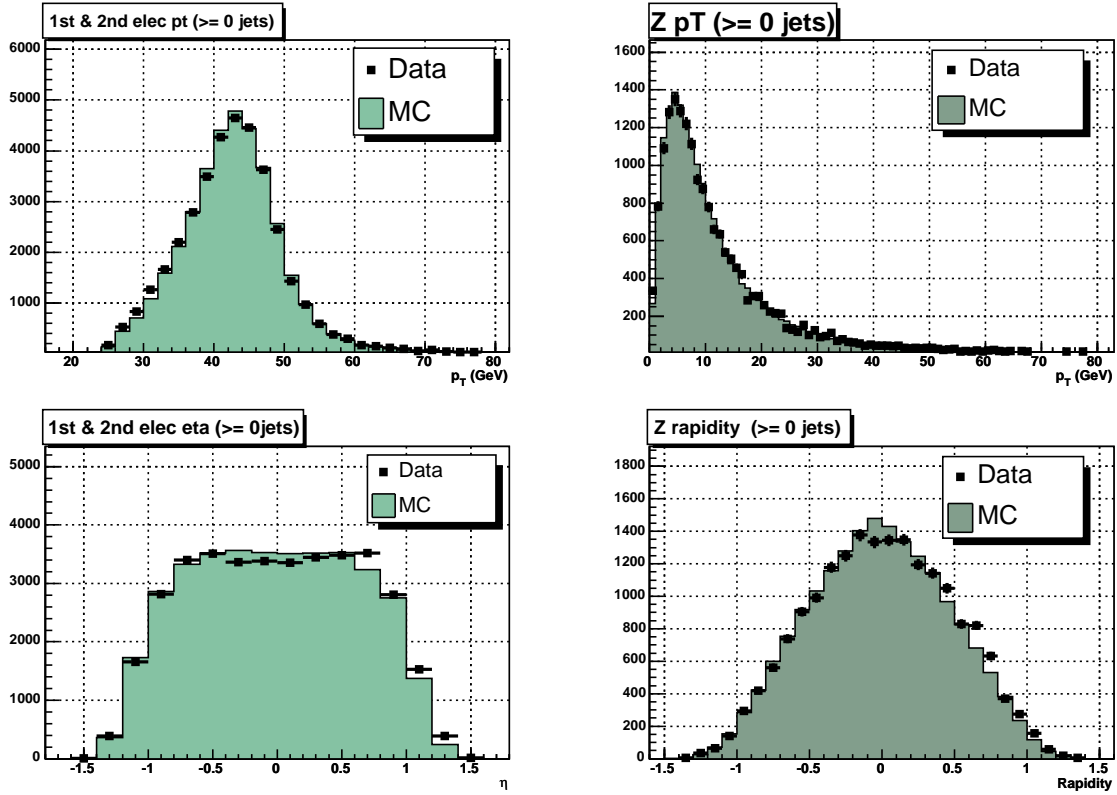
Figure 32. pT of both Z electrons (top left), physics η of both Z electrons (bottom left), Z p_T (top right), Z rapidity (bottom right) for the $Z/\gamma^* \to e^+e^-$ inclusive sample in data and MC (PYTHIA).

and Z kinematic properties [1]. Figure 33 compares the diem invariant mass distribution. The average Z mass is 91.02 GeV with a width of 4.03 GeV.

---

[1]We observe an excess of events in the electron η distribution at η =-0.5 and η=0.7. This feature is still under investigation and is also present in other DØ analyses.
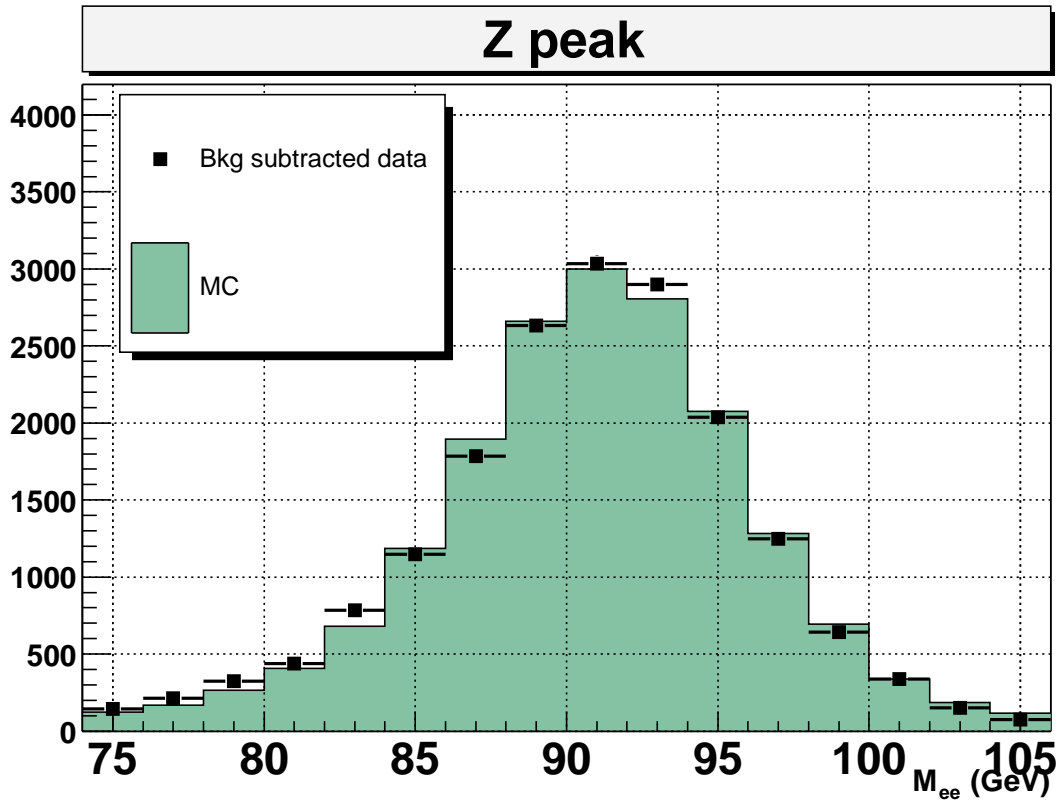
Figure 33. Diem invariant mass comparison for the $Z/\gamma^* \to e^+e^-$ inclusive sample in data and MC (PYTHIA). Data is background subtracted.

6.3.3.2 $\underline{Z/\gamma^* \rightarrow e^+e^- + \geq 1 \text{ Jet Sample}}$

Figure 34 shows comparisons of basic electron and Z distributions, Figure 35 shows a comparison of the diem invariant mass peak and Figure 36 and Figure 37 show comparisons of basic jet distributions [1].

6.3.3.3 $\underline{Z/\gamma^* \rightarrow e^+e^- + \geq 2 \text{ Jet Sample}}$

Figure 38 shows comparisons of basic electron and Z distributions, Figure 39 shows a comparison of the diem invariant mass peak and Figure 40, Figure 41 and Figure 42 show comparisons of basic jet distributions.

---

[1]We observe an excess of events in the jet η distributions at η =-0.4. This feature is still under investigation. We checked η_{det} vs ϕ_{det} and η_{det} vs p_T distributions. The feature was more pronounced in the initial Pass 1 dataset of the analysis.
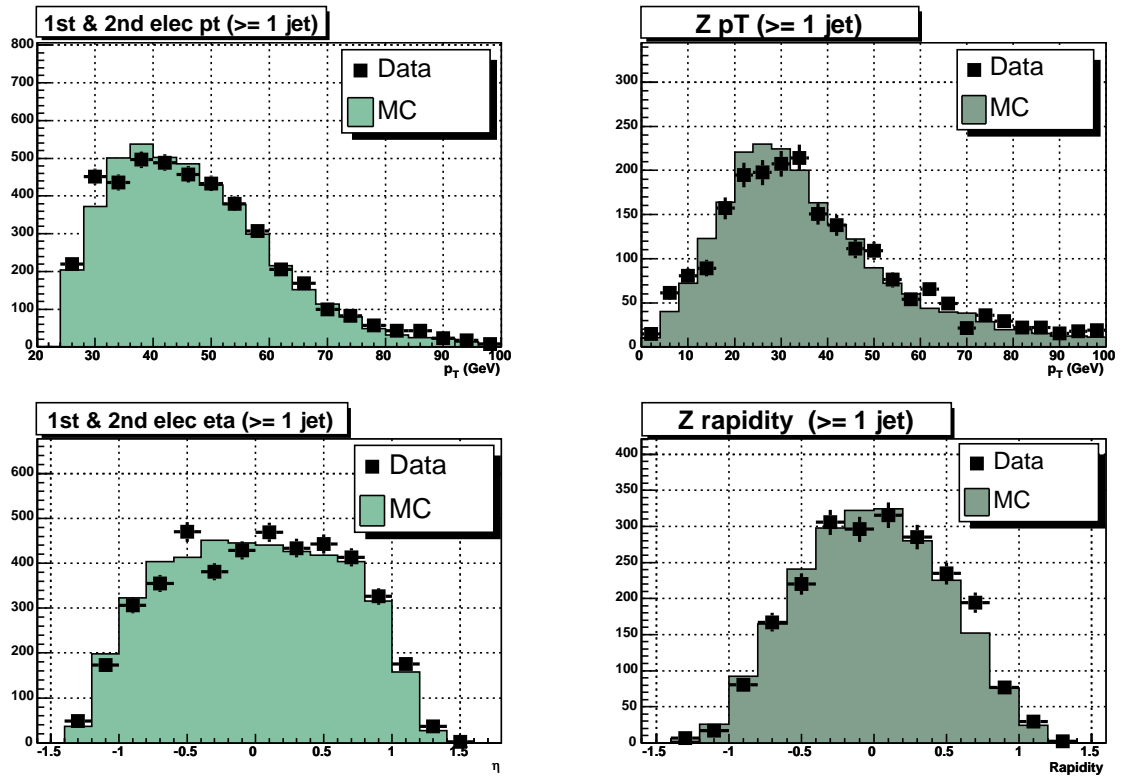
Figure 34. pT of both Z electrons (top left), physics η of both Z electrons (bottom left), Z p_T (top right), Z rapidity (bottom right) for the $Z/\gamma^* \rightarrow e^+e^- + \geq 1$ jet sample in data and MC (ALPGEN).
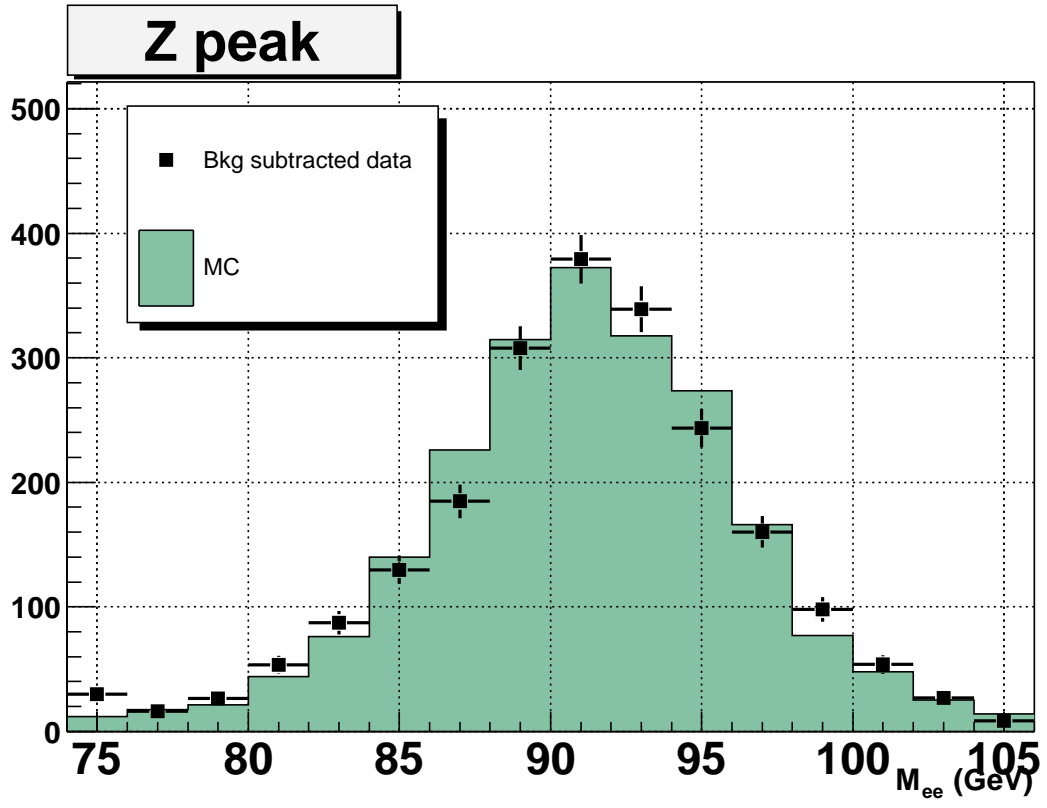
Figure 35. Diem invariant mass comparison for the $Z/\gamma^* \to e^+e^- + \geq 1$ jet sample in data and MC (ALPGEN). Data is background subtracted.
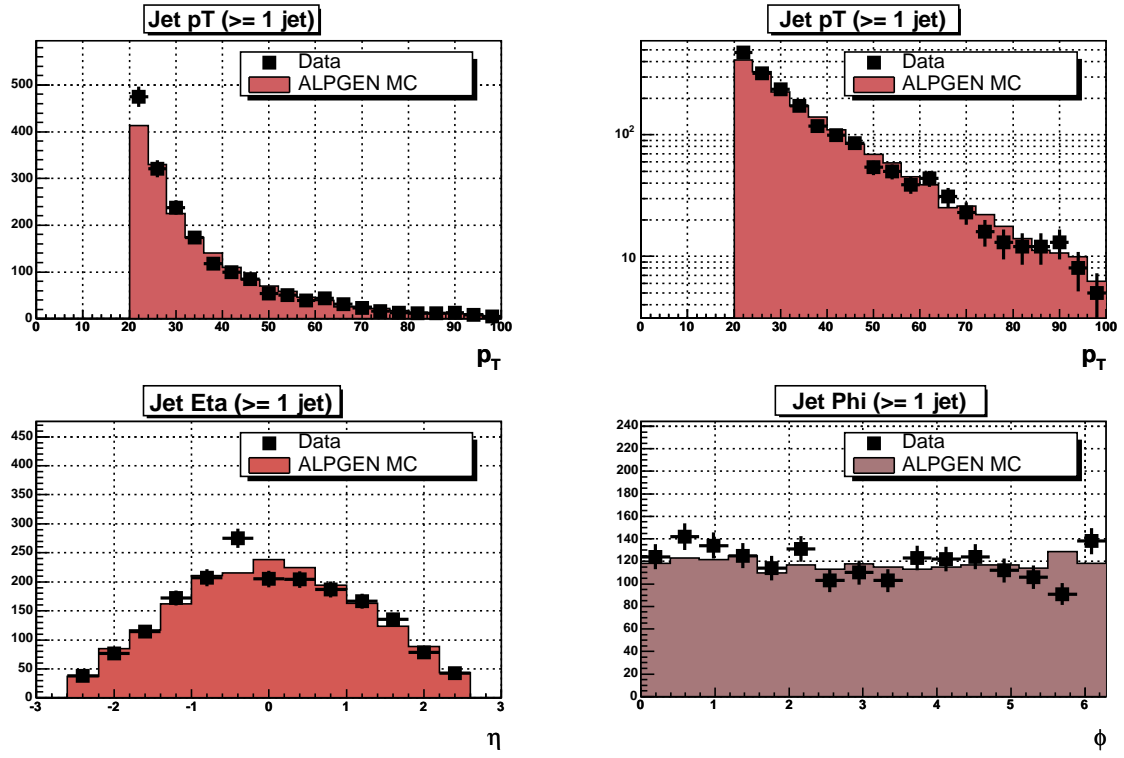
Figure 36. p_T (linear and logarithmic), physics η and physics Φ of all jets for the $Z/\gamma^* \rightarrow e^+e^- + \geq 1$ jet sample in data and MC (ALPGEN).
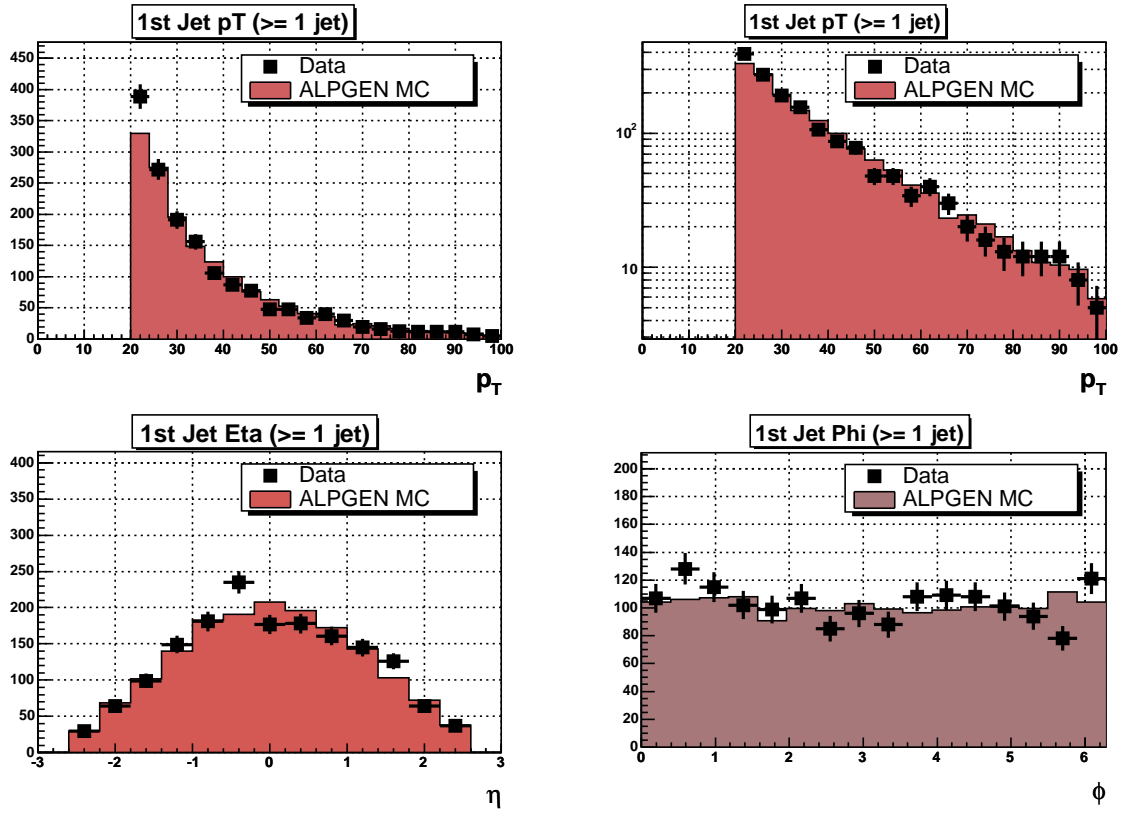
Figure 37. p_T (linear and logarithmic), physics η and physics Φ of the leading jets for the $Z/\gamma^* \rightarrow e^+e^- + \geq 1$ jet sample in data and MC (ALPGEN).
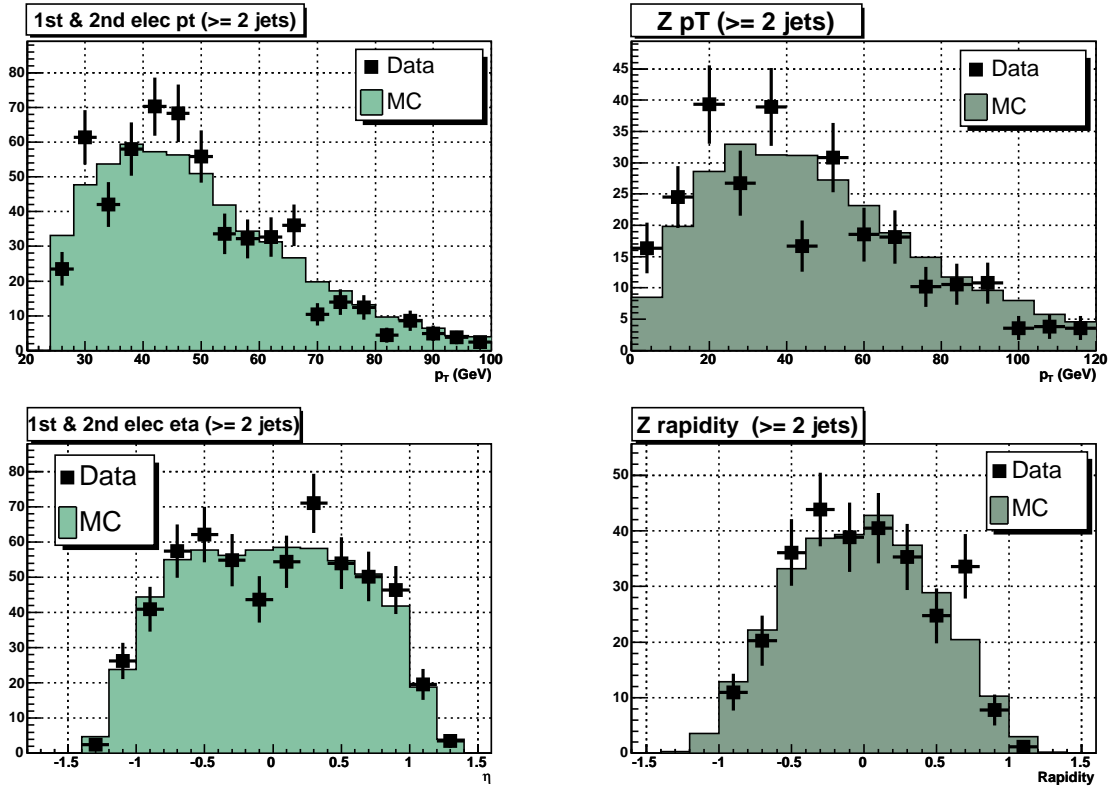
Figure 38. pT of both Z electrons (top left), physics η of both Z electrons (bottom left), Z p_T (top right), Z rapidity (bottom right) for the $Z/\gamma^* \to e^+e^- + \geq 2$ jet sample in data and MC (ALPGEN).
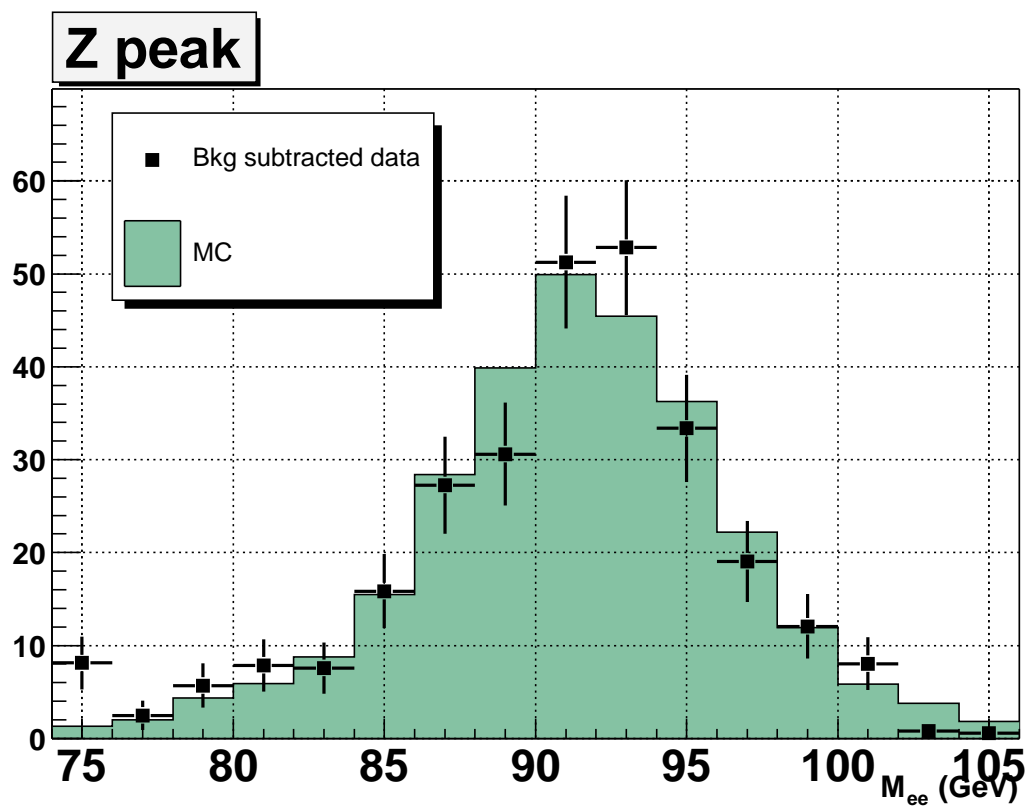
Figure 39. Diem invariant mass comparison for the $Z/\gamma^* \to e^+ e^- + \geq 2$ jet sample in data and MC (ALPGEN). Data is background subtracted.
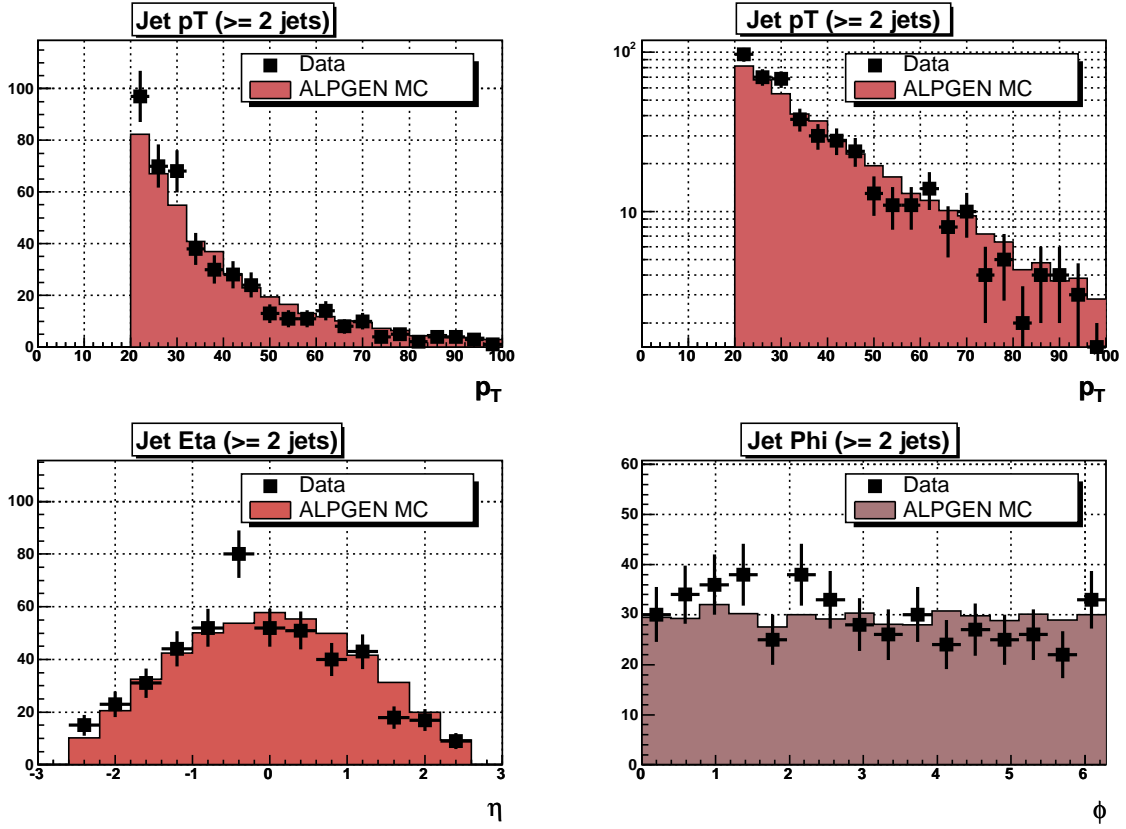
Figure 40. p_T (linear and logarithmic), physics η and physics Φ of all jets for the $Z/\gamma^* \to e^+e^- + \geq 2$ jet sample in data and MC (ALPGEN).
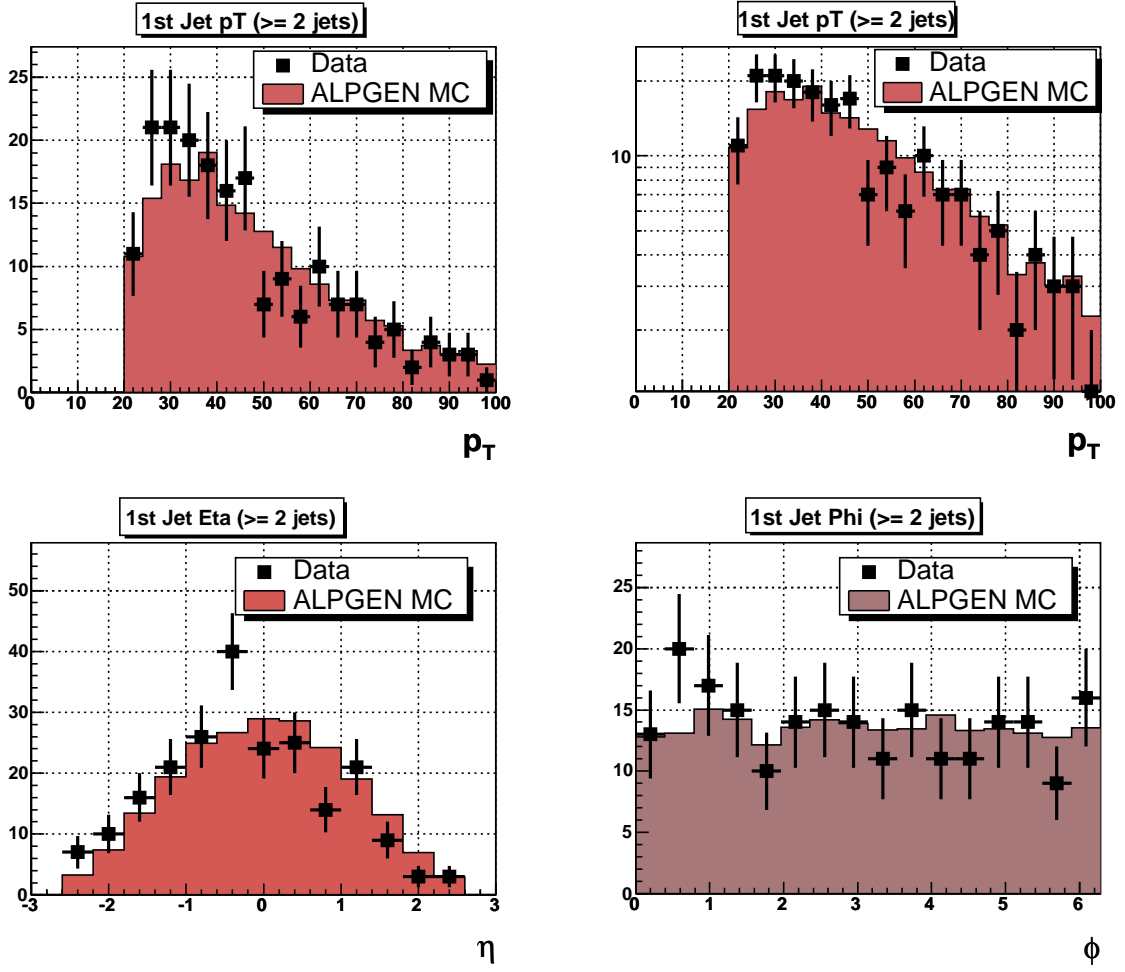
Figure 41. p_T (linear and logarithmic), physics η and physics Φ of the leading jets for the $Z/\gamma^* \to e^+e^- + \geq 2$ jet sample in data and MC (ALPGEN).
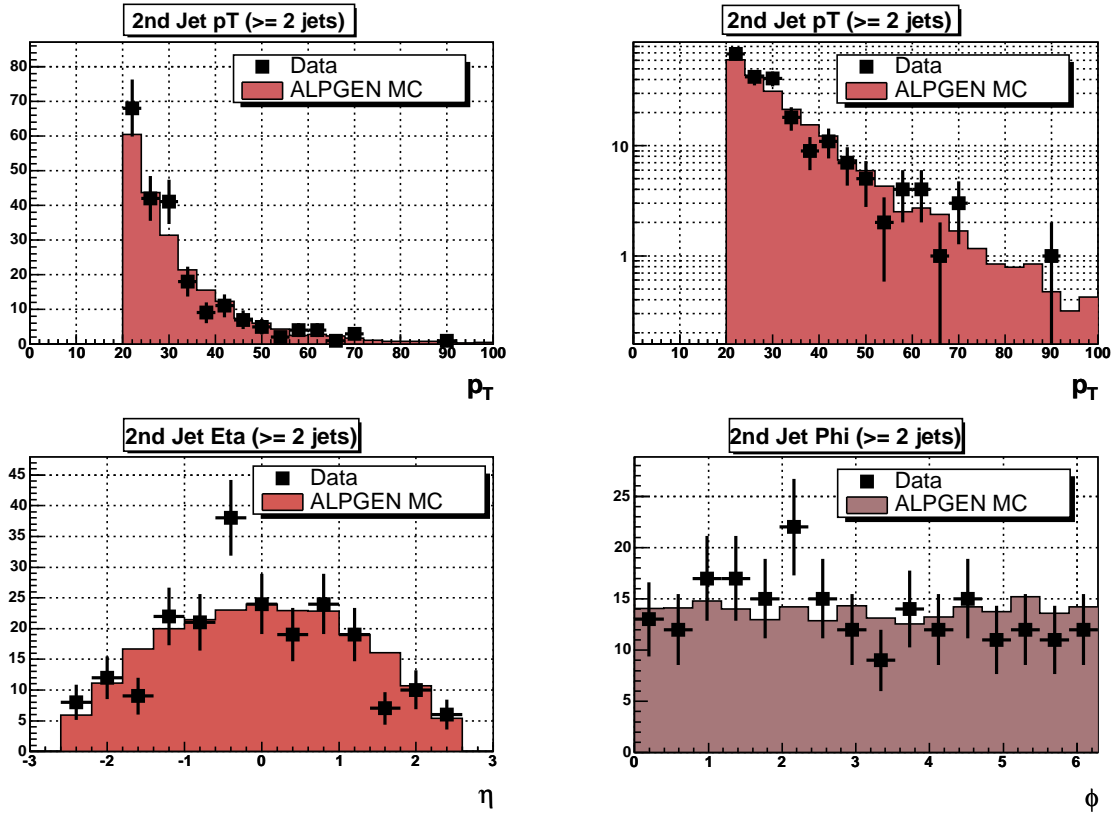
Figure 42. p_T (linear and logarithmic), physics η and physics Φ of the next to leading jets for the $Z/\gamma^* \to e^+e^- + \geq 2$ jet sample in data and MC (ALPGEN).

6.4 $Z/\gamma^* \rightarrow e^+e^-$ Inclusive Cross Section

In order to determine the $Z/\gamma^* \rightarrow e^+e^-$ inclusive cross section we evaluate the following equation:

$$\sigma \times \mathrm{BR}(Z/\gamma^* \rightarrow e^+e^-) = \frac{N - B}{\mathcal{L} \times \varepsilon} \qquad (6.3)$$

$N - B$ is the number of signal events after background subtraction. The total integrated luminosity of the dataset $\mathcal{L}$ is approximately 343 pb^{-1}.

The efficiency ε to measure e^+e^- pairs coming from Z/γ^* decays can be split up into the following contributions (Equation 6.4):

$$\varepsilon_{tot} = \varepsilon_{trigger} \cdot \varepsilon_{EM} \cdot \varepsilon_{track} \cdot \varepsilon_{acceptance} \qquad (6.4)$$

where $\varepsilon_{trigger}$ is the efficiency of the event to have at least one electron to pass all trigger levels, ε_{EM} is the efficiency of reconstructing two EM clusters which pass all electron ID cuts, ε_{track} is the efficiency of finding at least one track which matches an EM cluster and $\varepsilon_{acceptance}$ is the efficiency of the kinematic and geometric electron cuts, the diem invariant mass cut and the primary vertex cut.

6.4.1 Efficiencies

6.4.1.1 Trigger Efficiency

The combined efficiency of all triggers per electron is studied with a tag-and-probe method using Z candidate events with invariant mass between 70 and 110 GeV. For this method, both Z candidate electrons are considered as possible "tags". An electron becomes a "tag" if it

passes trigger requirements for at least one unprescaled trigger in the trigger combination. To pass the requirements of a trigger, an electron must have a matching trigger object at each level which passes all cuts for the corresponding trigger. Both the tag and probe electrons must satisfy the following requirements:

- $p_T > 20$ GeV

- EM Fraction > 0.9

- Isolation < 0.15

- H-Matrix(7) < 12

- Track match with $P(\chi^2) > 0.01$

The probe electron must have matching trigger objects at L1, L2 and L3 within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ of 0.4.

Trigger efficiencies are parameterized versus EM object p_T and derived separately for pre-v12 and v12 data. In cases where the L2 subsystem was not present (all runs with run numbers $\leq 169{,}523$) only L1 and L3 trigger objects were used. The average trigger efficiencies for the pre-v12 and v12 datasets are (with statistical errors):

- $\varepsilon_{pre-v12}(\text{Trigger}) = 94.6\% \pm 0.3\%$

- $\varepsilon_{v12}(\text{Trigger}) = 98.2\% \pm 0.1\%$

Figure 43 shows the parameterized trigger efficiencies for both datasets.

We correct for trigger inefficiencies in the following way:

- In a given event we use the trigger efficiency curves to get the trigger efficiencies ε_1 and ε_2 for the two EM objects (based on p_T).

- To get the event based trigger efficiency, we need to take into account all permutations for the two EM objects to fire a trigger:

$$\varepsilon_{trigger} = \varepsilon_1 \cdot (1 - \varepsilon_2) + \varepsilon_2 \cdot (1 - \varepsilon_1) + \varepsilon_1 \cdot \varepsilon_2 = \varepsilon_1 + \varepsilon_2 - \varepsilon_1 \cdot \varepsilon_2 \qquad (6.5)$$

- The inverse of $\varepsilon_{trigger}$ is applied as a corrective weight when we fill the diem invariant mass histogram.

- We use the corrected diem invariant mass histogram to derive the number of signal events for the cross section calculation.

6.4.1.2   EM Reconstruction and Identification Efficiency

To determine EM efficiencies a tag and probe method is used where the tag leg consists of an electron candidate and the probe leg of a track. The tag electron must pass all the electron selection cuts, have a good track match and satisfy trigger requirements for the event. There must also be a second track (probe track) in the event. Both tag- and probe-tracks must pass the following selection criteria (44):

- stereo track[1]

- 25 GeV $< p_T <$ 80 GeV

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[1]Requiring hits in stereo layers of the tracking system.
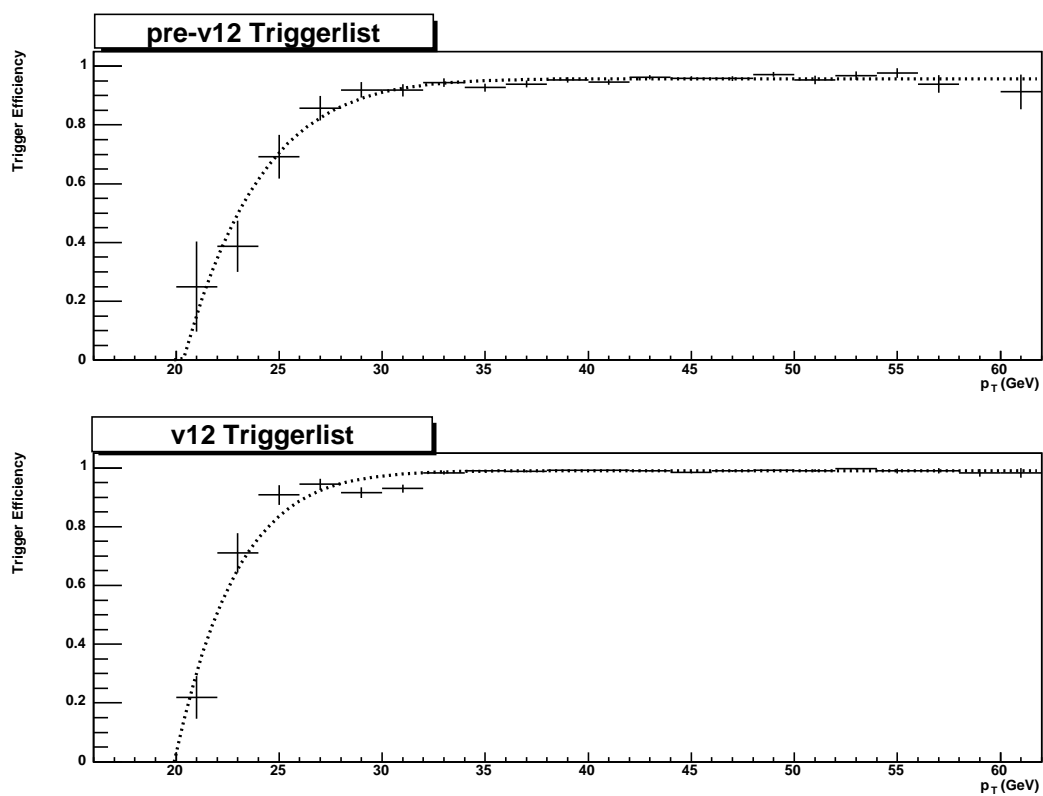
Figure 43. Trigger efficiencies for pre-v12 (top) and v12 (bottom) datasets vs EM object p_T

- χ^2 probability for best track < 8 (using the distance in η/Φ and E/p)

- Distance of closest approach between track and beam position in the R-Φ plane < 0.3cm

- Δz_{vertex} of the two tracks < 4cm

- $|\eta_{detector}| < 1.1$

Tag electron selection criteria:

- ID $= 10$ or ± 11

- EMFraction > 0.9

- Isolation < 0.15

- H-Matrix(7) < 12

- $p_T > 25$ GeV

- $|\eta_{det}| < 1.1$

- No fiducial restrictions in ϕ

- Matched with tag track within $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = \sqrt{0.1^2 + 0.1^2}$ of 0.14

- Must have fired the trigger

Ways to reduce possible background contamination:

- tag- and probe-tracks are required to have opposite signs

- Missing $E_T < 15$ GeV

Additional requirements:

- $|PVZ| < 60$ cm

- Tag-electron-probe-track invariant mass cut: 70 GeV $< M_{ee} <$ 110 GeV

- Sideband background subtraction (only used to derive average efficiencies).

Once an event is found which satisfies all of the above requirements, a denominator histogram is filled, i.e. probe track ϕ and p_T histograms for parameterized efficiencies and tag-electron-probe-track diem invariant mass histograms for average efficiencies. In the case a reconstructed EM cluster is found nearby the probe-track ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = \sqrt{0.1^2 + 0.1^2} = 0.14$) which passes the EMID cuts (HMx, EMF, Iso), the respective numerator histogram is filled.

The average EM reco and ID efficiencies in data and MC are (with statistical errors):

- $\varepsilon_{data}(\text{EM}) = 88.9\% \pm 0.3\%$

- $\varepsilon_{MC}(\text{EM}) = 93.1\% \pm 0.1\%$

For average efficiencies we reduce the background to a minimum by requiring opposite sign tracks and missing $E_T < 15$ GeV. In addition we subtract background using the sidebands in the tag-electron-probe-track invariant mass distribution. As a cross check we derive the average efficiency in data without sideband background subtraction. The result is within 1% of the sideband subtracted value: $88.2\% \pm 0.2\%$.

Figure 44 and Figure 45 show the EM efficiencies for data and MC in a one-dimensional parameterization.

We correct for EM inefficiencies in the following way:

- In a given event we use two-dimensional efficiency curves (versus p_T and Φ) to estimate the EM efficiencies ε_1 and ε_2 for the two EM objects (based on their p_T and Φ).

- To estimate the event based EM efficiency we take the product of ε_1 and ε_2:

$$\varepsilon_{EM} = \varepsilon_1 \cdot \varepsilon_2 \tag{6.6}$$

- The inverse of ε_{EM} is applied as a corrective weight when we fill the diem invariant mass histogram.

6.4.1.3 <u>EM-Track Match Efficiency</u>

Average track finding and matching efficiencies are derived using diem invariant mass histograms (Figure 46 to Figure 49).

Using a convolution of a Gaussian and Breit-Wigner fit for the Z peak and an exponential shape to describe the QCD and Drell-Yan contributions, we extract the number of events under the Z peak from the four diem invariant mass histograms: $N_{1trk}(data)$, $N_{2trk}(data)$, $N_{1trk}(MC)$ and $N_{2trk}(MC)$. $N_{1trk}(data)$ and $N_{1trk}(MC)$ are the number of Z candidates when requiring at least one track match in data and MC; $N_{2trk}(data)$ and $N_{2trk}(MC)$ are the number of Z candidates when requiring exactly two track matches in data and MC. We use these numbers to estimate the average track finding and matching efficiencies in data and MC:

$$\varepsilon_{data}(\text{Tracking}) = \frac{2 \cdot N_{2trk}(data)}{N_{2trk}(data) + N_{1trk}(data)} = 77.1\% \pm 0.3\% \tag{6.7}$$
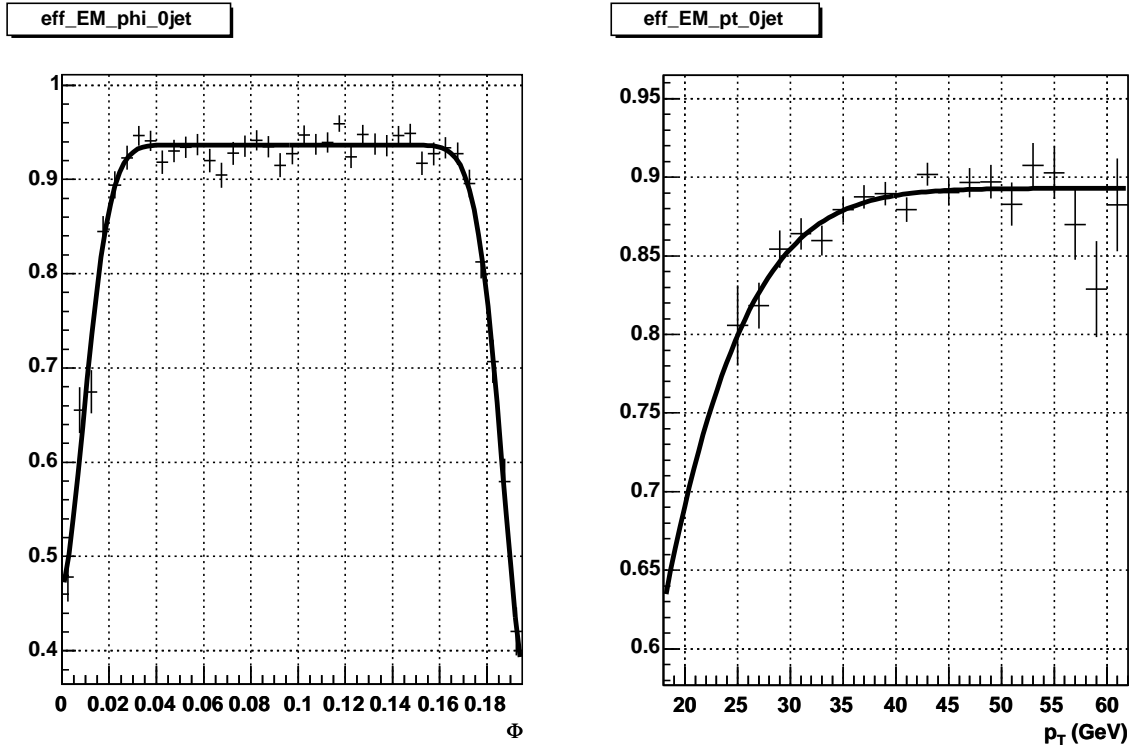
Figure 44. EM efficiencies versus probe track Φ and p_T in data. The Φ distribution shows the modulus(Φ, $\frac{2\pi}{32}$) distribution to illustrate the effect of the calorimeter Φ-module boundaries.
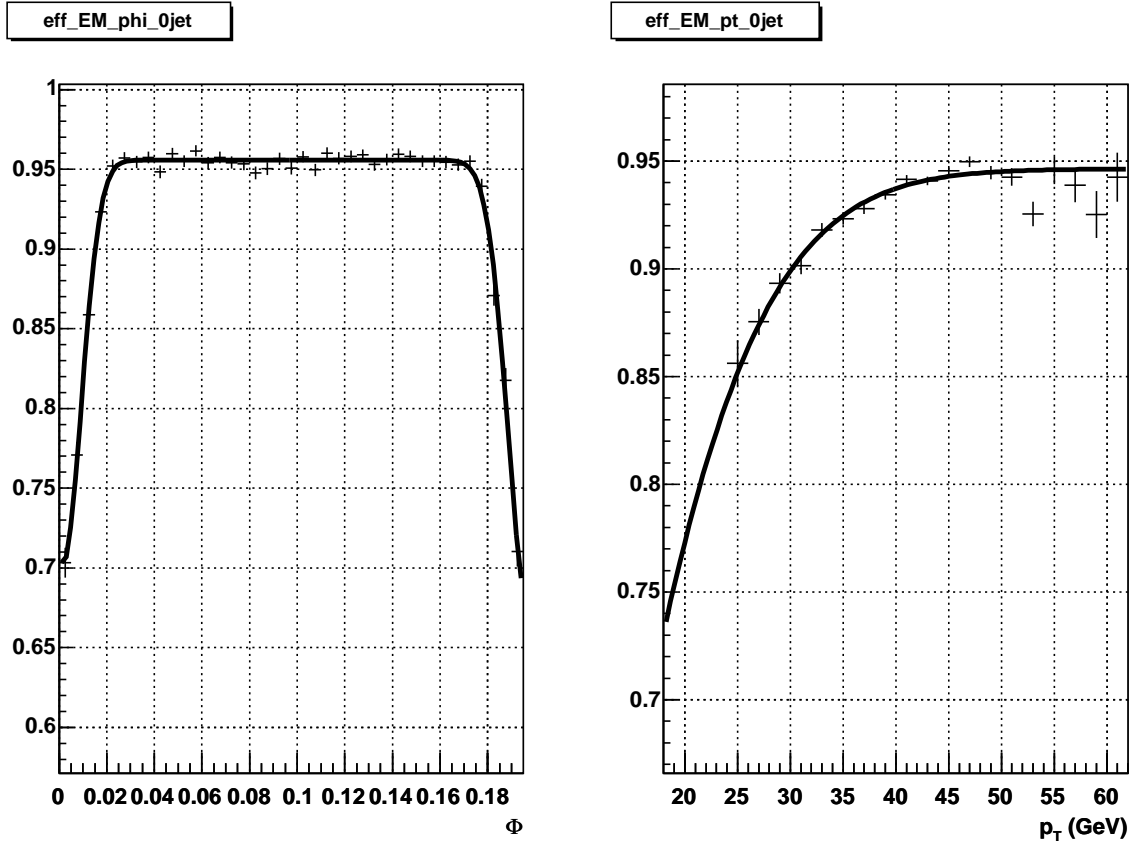
Figure 45. EM efficiencies versus probe track Φ and p_T in MC. The Φ distribution shows the modulus(Φ, $\frac{2\pi}{32}$) distribution to illustrate the effect of the calorimeter Φ-module boundaries.

$$\varepsilon_{MC}(\text{Tracking}) = \frac{2 \cdot N_{2trk}(MC)}{N_{2trk}(MC) + N_{1trk}(MC)} = 87.8\% \pm 0.03\% \qquad (6.8)$$

We correct for the tracking inefficiencies in the following way:

- In each event we use the average tracking efficiency $\varepsilon_{average}$.

- To get the event based tracking efficiency we need to take all permutations for one or two tracks into account:

$$\varepsilon_{tracking} = 2 \cdot \varepsilon_{average}(1 - \varepsilon_{average}) + \varepsilon_{average}^2 = 2 \cdot \varepsilon_{average} - \varepsilon_{average}^2 \qquad (6.9)$$

- The inverse of $\varepsilon_{tracking}$ is applied as a corrective weight when we fill the diem invariant mass histogram.

6.4.1.4   <u>Acceptance</u>

We use the $Z/\gamma^* \to e^+e^-$ PYTHIA MC sample to estimate the acceptance. The numerator contains the number of events satisfying the following requirements at the reconstructed level:

- Primary vertex cut: $|PVZ| < 60$ cm

- Electron cuts: $p_T > 25$ GeV and $|\eta| < 1.1$

- Diem invariant mass cut: 75 GeV $< M_{ee} < 105$ GeV
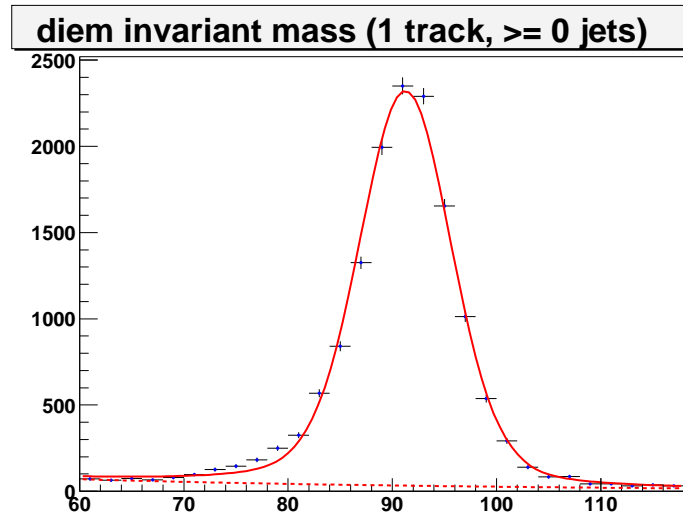
Figure 46. Invariant mass in data when requiring at least one track-matched electron.
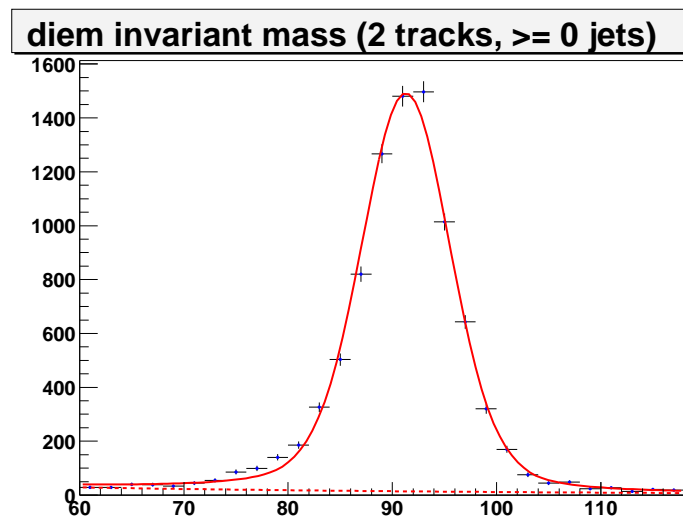
Figure 47. Invariant mass in data when requiring two track-matched electrons.
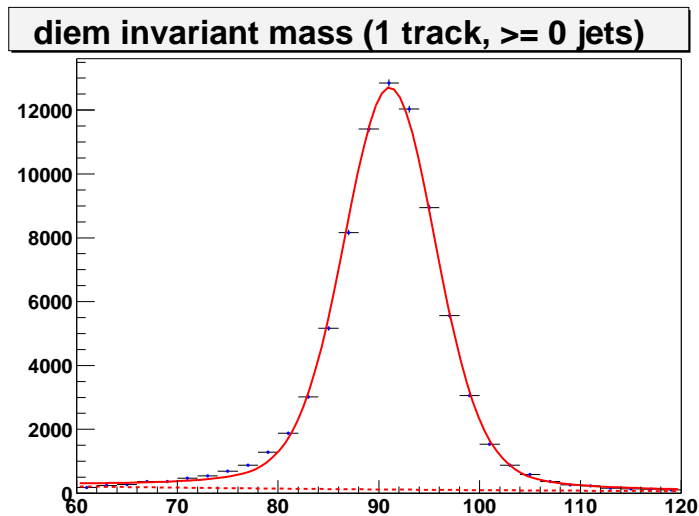
Figure 48. Invariant mass in MC when requiring at least one track-matched electron.
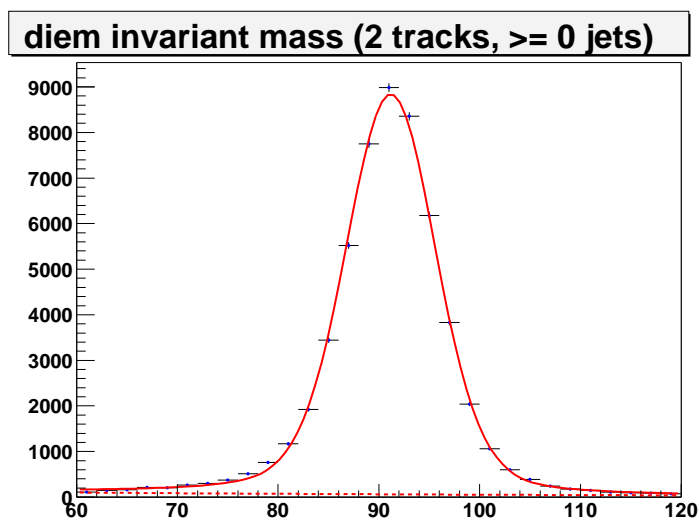
Figure 49. Invariant mass in MC when requiring two track-matched electrons.

The denominator contains the number of events with generated Z/γ^* particles that are within the diem invariant mass window.

We estimate the acceptance with statistical error for inclusive $Z/\gamma^* \to e^+e^-$ to be:

$$\text{Acceptance}(Z/\gamma^* \to e^+e^- + \text{X}) = 21.4\% \pm 0.1\% \tag{6.10}$$

Since the numerator in the acceptance calculation involves two reconstructed electrons, we apply a corrective weight to the numerator. Based on the p_T and Φ values of the two electrons, we estimate their reconstruction efficiencies (98% on average). The product of the inverse of those reconstruction efficiencies yields the corrective weight. We also apply the Z p_T correction factor (see Chapter 6.3.2) as an additional weight in both numerator and denominator of the acceptance.

6.4.2   Cross section calculation

After applying all corrections we estimate the number of (corrected) signal events from the diem invariant mass distribution (Figure 50). We fit a convolution of a Gaussian and Breit-Wigner shape to the Z peak and an exponential shape to describe the QCD and Drell-Yan contributions. We justify the choice of using an exponential shape for the QCD background by looking at the diem invariant mass distribution of EM object pairs that were selected by applying "anti-electron cuts":

- All criteria that are applied to loose electron candidates as described in Section 6.2.2 except for the H-Matrix cut.

- H-Matrix(7) > 35

- Two of these objects per event.

In this way we select two jets with high electromagnetic energy content in the shower.

Since the Drell-Yan component is part of our signal, we need to disentangle the QCD component from the Drell-Yan component. Using the inclusive $Z/\gamma^* \to e^+e^-$ PYTHIA MC sample we determine the percentage of Drell-Yan events in $Z/\gamma^* \to e^+e^-$ decays by fitting a Gaussian and Breit-Wigner shape to the Z component and an exponential shape to the Drell-Yan component. We find that 2.06% of the events in the inclusive $Z/\gamma^* \to e^+e^-$ sample are due to Drell-Yan.

Based on these fits we extract the number of signal events from direct Z Boson and Drell-Yan decays as well as the number of QCD background events in the diem invariant mass signal window (75 GeV $< M_{ee} <$ 105 GeV) [1]:

- Number of signal events from Z Boson and Drell-Yan decays = 18,263.8

- Number of QCD background events = 407.5

Based on the integrated luminosity (343 pb^{-1}) and the acceptance (21.4%) we calculate the inclusive $Z/\gamma^* \to e^+e^-$ cross section:

$$\sigma \times \mathrm{BR}(Z/\gamma^* \to e^+e^-) = \frac{N-B}{\mathcal{L} \times A} = 248.9 \text{ pb } \pm 2.5(\mathrm{stat}) \tag{6.11}$$

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[1]The number of signal events is derived by counting all entries for a particular M_{ee} bin and subtracting from it the number of entries from the background fit.

diem invariant mass (1 track, >= 0 jets)
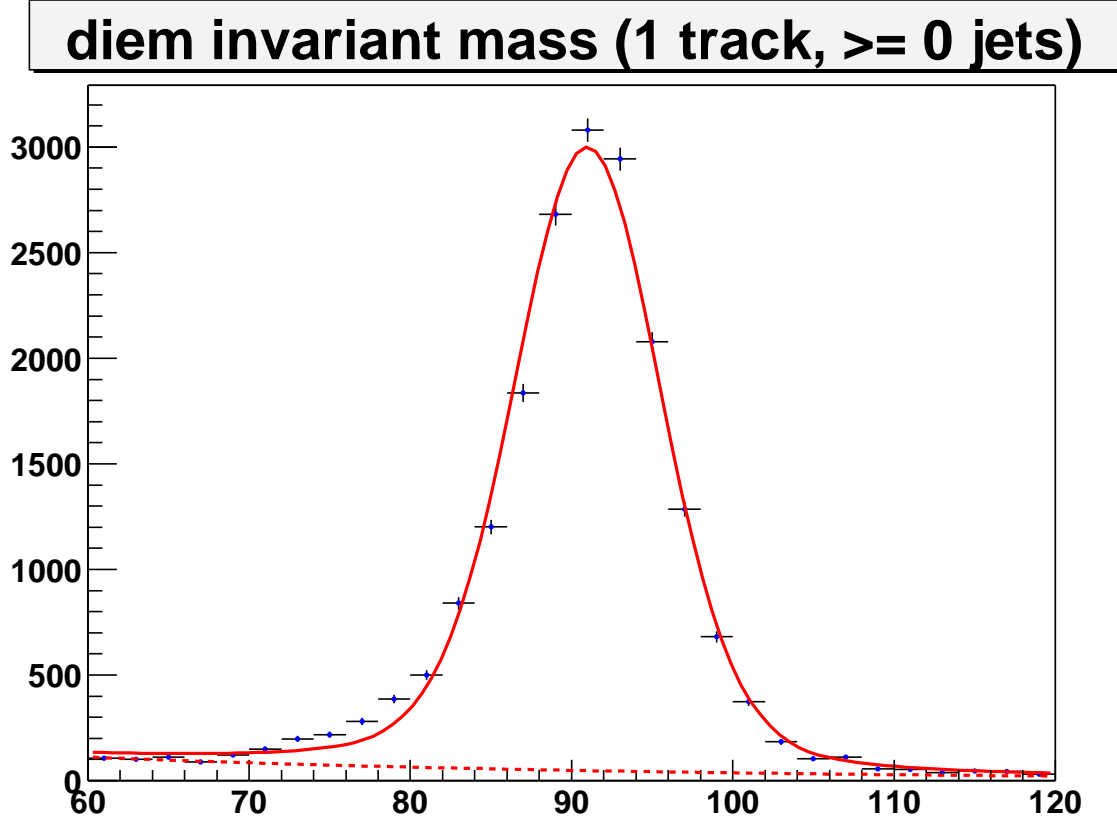
Figure 50. Diem invariant mass distribution for $Z/\gamma^* \to e^+e^- + X$ (Mean = 91.02 GeV ± 0.04 GeV, Width 4.03 GeV ± 0.04 GeV).

In addition a MC closure test is performed. Going through the entire procedure using MC parameters only, we calculate a cross section of 179 pb with a MC input cross section of 183 pb.

Jet multiplicity	pre-v12	v12
≥ 0	$94.6\% \pm 0.3\% \pm 5.0\%$	$98.2\% \pm 0.1\% \pm 5.0\%$
≥ 1	$93.1\% \pm 1.0\% \pm 5.0\%$	$96.9\% \pm 0.5\% \pm 5.0\%$
≥ 2	$95.2\% \pm 2.1\% \pm 5.0\%$	$95.5\% \pm 1.7\% \pm 5.0\%$

TABLE V

OBJECT BASED TRIGGER EFFICIENCIES WITH STATISTICAL AND SYSTEMATIC ERRORS (RESPECTIVELY) FOR THE PRE-V12 AND V12 DATASETS FOR DIFFERENT INCLUSIVE JET MULTIPLICITIES.

6.5 $Z/\gamma^* \rightarrow e^+e^- + \geq n$ Jets Cross Section

6.5.1 Efficiencies vs Jet Multiplicity

In the following chapters we use the PYTHIA MC sample to derive corrections for the inclusive sample, and ALPGEN MC samples for the n-jet corrections.

6.5.1.1 Trigger Efficiency

We do not observe significant variations in the trigger efficiencies as jet activity increases (Figure 51). Therefore the same trigger corrections as for the inclusive sample are applied (see Chapter 6.4.1.1). Table V summarizes electron trigger efficiencies for the pre-v12 and v12 datasets for different inclusive jet multiplicities. We assign an additional systematic error of $\pm5\%$ for all jet multiplicities.

6.5.1.2 EM Reconstruction and Identification Efficiency

We apply the same EM corrections as for the inclusive sample to each jet multiplicity sample (see Chapter 6.4.1.2). In addition we estimate residual inefficiencies due to additional
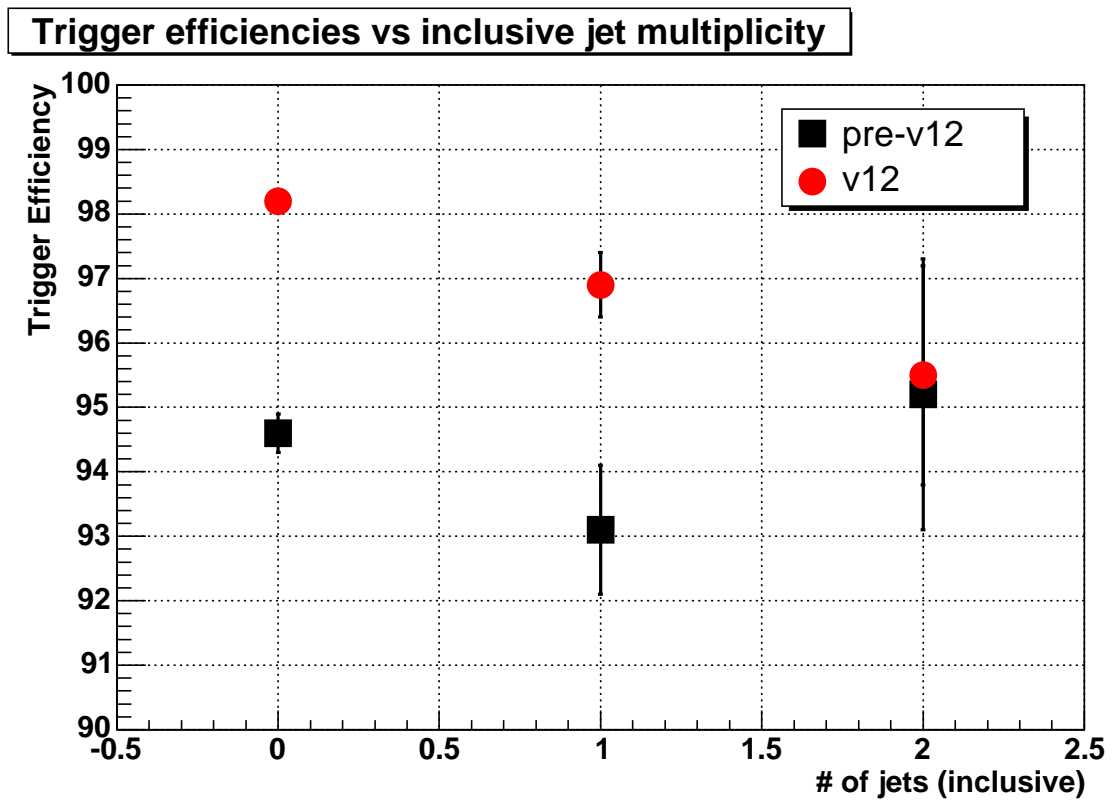
Figure 51. Average object based trigger efficiencies in data versus inclusive jet multiplicity.

Jet multiplicity	data	MC
≥ 0	$88.9\% \pm 0.3\% \pm 3.0\%$	$93.1\% \pm 0.1\%$
≥ 1	$87.2\% \pm 1.0\% \pm 3.0\%$	$92.3\% \pm 0.3\%$
≥ 2	$90.0\% \pm 2.5\% \pm 3.0\%$	$91.2\% \pm 1.0\%$
≥ 3	(n/a)	$90.1\% \pm 3.5\%$

TABLE VI

OBJECT BASED EM RECO AND ID EFFICIENCIES WITH STATISTICAL AND
SYSTEMATIC ERRORS (RESPECTIVELY) IN DATA AND MC FOR DIFFERENT
INCLUSIVE JET MULTIPLICITIES. THERE WAS NOT ENOUGH STATISTICS
AVAILABLE TO ESTIMATE THE EM EFFICIENCY IN DATA FOR ≥ 3 JETS.

jet activity by looking at the distribution of average electron EM reco and ID efficiencies versus

jet multiplicity (Figure 52). The averaged efficiencies are derived using the procedure outlined

in Chapter 6.4.1.2 for data and MC samples of different jet multiplicities.

Table VI summarizes the electron EM reco and ID efficiencies in data and MC for different

jet multiplicities. No significant change of the average efficiencies with respect to jet multiplicity

is observed in data. Therefore no additional correction is applied. Due to the variation of the

various efficiencies a systematic error of $\pm 3\%$ is assigned for all jet multiplicities.

Based on the drop in MC we apply a factor of 1.02^2 as a corrective weight to each event.

This value is derived by taking the ratio of the EM efficiency for the inclusive sample and the

average of the EM efficiencies for the 1-jet, 2-jet and 3-jet samples.
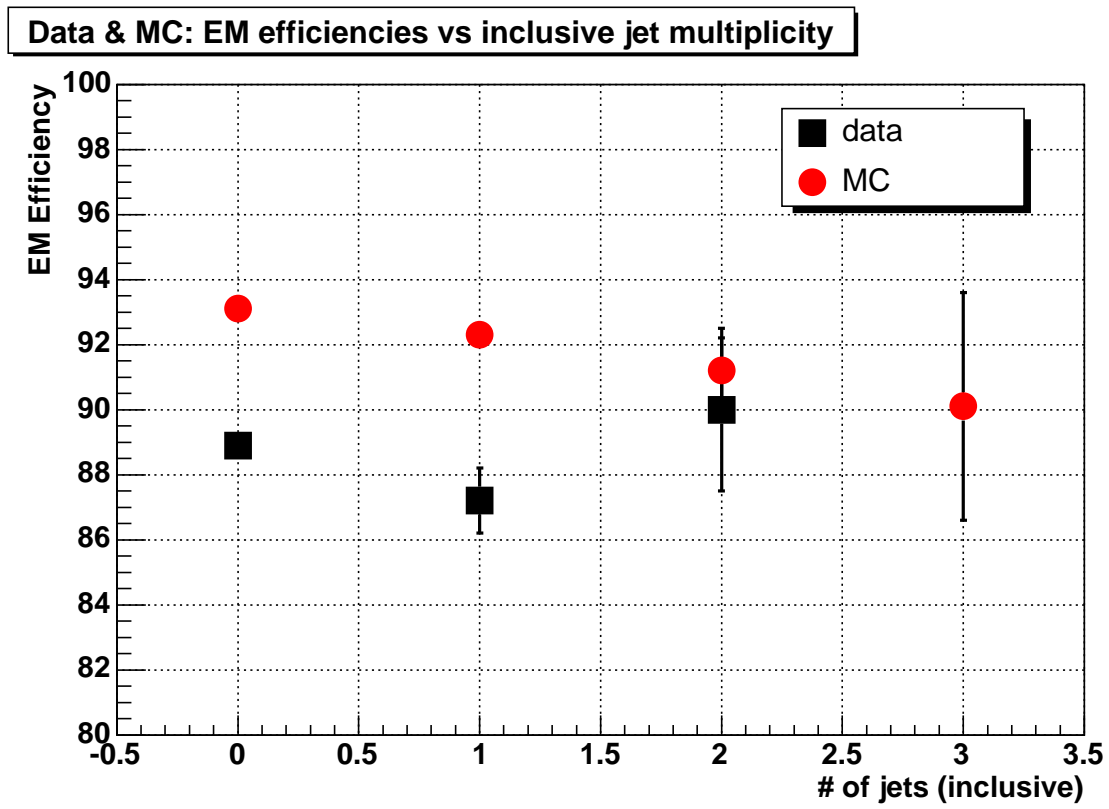
Figure 52. Average object based EM reco and ID efficiencies in data and MC versus inclusive jet multiplicity.

Jet multiplicity	data	MC
≥ 0	$77.1\% \pm 0.3\%$	$87.8\% \pm 0.03\%$
≥ 1	$74.5\% \pm 0.9\%$	$87.7\% \pm 0.3\%$
≥ 2	$72.1\% \pm 2.5\%$	$87.5\% \pm 0.9\%$

TABLE VII

OBJECT BASED TRACKING EFFICIENCIES WITH STATISTICAL ERRORS IN DATA
AND MC FOR DIFFERENT INCLUSIVE JET MULTIPLICITIES.

6.5.1.3   <u>EM-Track Match Efficiency</u>

Figure 53 and Table VII show the average object based tracking efficiencies for different jet multiplicities. In MC we use the value from the inclusive sample to correct for tracking inefficiencies for all jet multiplicities. In data we use the inclusive value for the inclusive sample, the 1-jet value for the 1-jet sample and the 2-jet value for all other jet samples.

Table VIII lists the systematic errors for the data efficiencies. For the 1-jet and 2-jet samples, we use the respective statistical errors as systematics. For the 3-jet, 4-jet and 5-jet samples, we add the 2-jet statistical error in quadrature with the difference between a linear fit to the available data points and the 2-jet efficiency value.
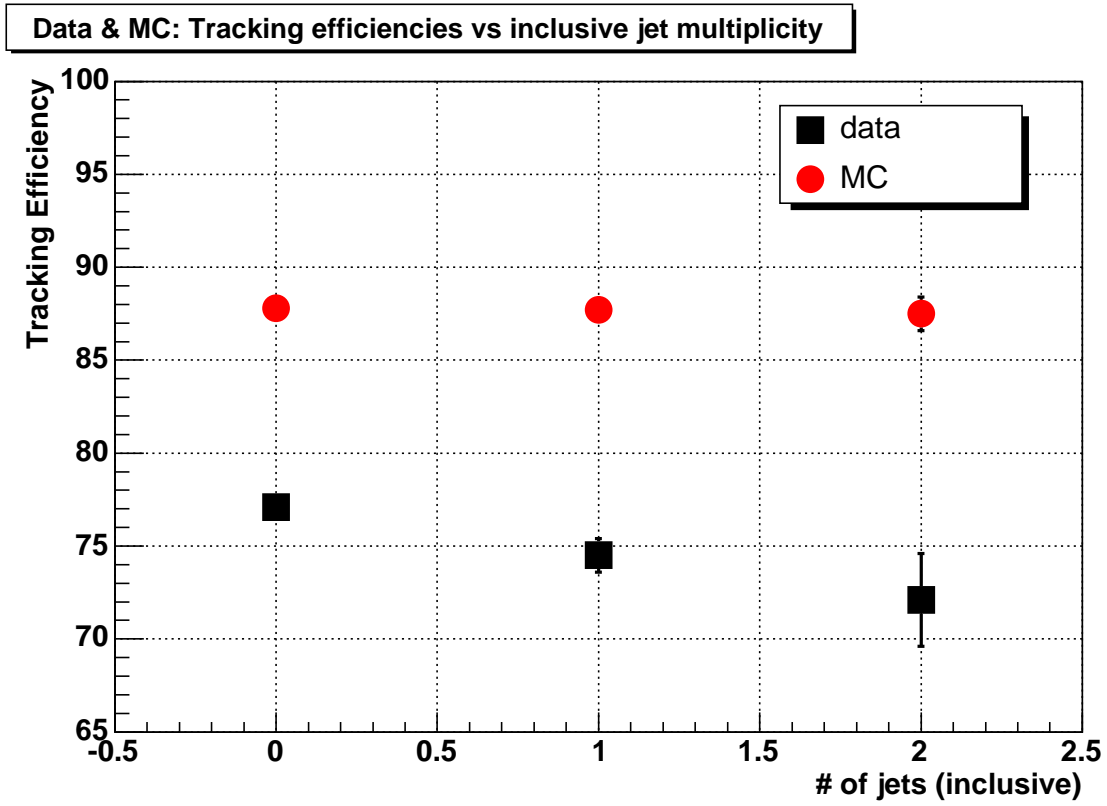
Figure 53. Average object based tracking efficiencies in data and MC versus inclusive jet multiplicity.

Jet multiplicity	Data Efficiency	Systematic Uncertainty
≥ 0	77.1%	$\pm 0.3\%$
≥ 1	74.5%	$\pm 0.9\%$
≥ 2	72.1%	$\pm 2.5\%$
≥ 3	72.1%	$\pm 3.5\%$
≥ 4	72.1%	$\pm 5.6\%$
≥ 5	72.1%	$\pm 7.9\%$

TABLE VIII

OBJECT BASED TRACKING EFFICIENCIES WITH SYSTEMATIC ERRORS.

6.5.1.4 <u>Acceptance</u>

We use the ALPGEN MC samples to estimate the acceptances for different jet multiplicities [1]. The numerator for the n-jet acceptance contains the number of events satisfying the following requirements:

- Primary vertex cut: $|PVZ| < 60$ cm

- Electron cuts: $p_T > 25$ GeV and $|\eta| < 1.1$

- Diem invariant mass cut: 75 GeV $< M_{ee} < 105$ GeV

- Particle level jet cut: n jets with $p_T > 20$ GeV and $|\eta| < 2.5$

The denominator for the n-jet acceptance contains the number of events satisfying the following requirements:

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[1] The $Z+3$ jet sample is used for jet multiplicities of 3, 4, and 5.

Jet multiplicity	Acceptance
≥ 0	$21.4\% \pm 0.1\%$
≥ 1	$25.1\% \pm 0.2\%$
≥ 2	$25.4\% \pm 0.2\%$
≥ 3	$27.4\% \pm 0.3\%$
≥ 4	$28.5\% \pm 0.7\%$
≥ 5	$30.3\% \pm 1.9\%$

TABLE IX

ACCEPTANCES WITH STATISTICAL ERRORS FOR DIFFERENT JET
MULTIPLICITIES.

- Generator level diem invariant mass cut: 75 GeV $< M_{ee} <$ 105 GeV

- Particle level jet cut: n jets with $p_T >$ 20 GeV and $|\eta| < 2.5$

No additional Z p_T correction is needed since the Z p_T distributions between data and ALPGEN

MC agree well (see Chapter 6.3.2). Table IX summarizes the acceptances for different jet

multiplicities.

6.5.1.5   Jet Reconstruction and Identification Efficiency

To estimate the jet reco/ID efficiency in data we use the "Z p_T balance" method to measure

the scaling factor needed to adjust the MC jet reco/ID efficiency to data, and then use MC to

measure the "straight" reco/ID jet efficiency with respect to the particle level jets (45). The

Z p_T balance method relies on the recoil of a jet against the Z boson. We select events with Z

candidates and search for a recoiling calorimeter jet opposite in Φ. We measure the "efficiency"

of finding a recoiling jet as a function of the Z p_T in data and MC. The ratio of these efficiencies

in data and MC gives us the scaling factor that we apply to the MC in order to make it agree with the data jet reco/ID efficiency. We then measure the straight jet reco/ID efficiency in MC by matching particle level jets with calorimeter jets within a search cone of $\Delta R = 0.4$. The jet reco/ID efficiency is plotted versus MC particle jet p_T. The p_T values of the particle jets are smeared with the data energy resolutions (see Chapter 6.1.2). Figure 54 shows the data jet reconstruction efficiencies for different regions in the calorimeter.
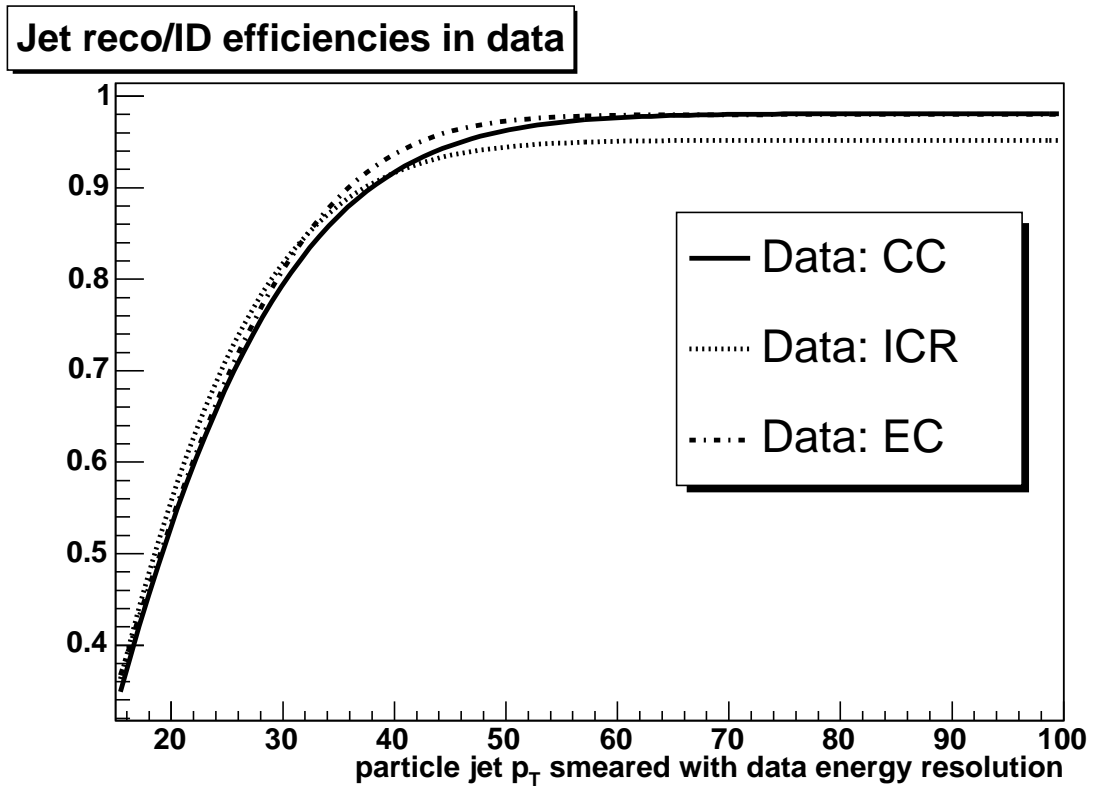
Figure 54. Jet reco/ID efficiencies in data. CC = $-0.7 < |\eta_{det}| < 0.7$, ICR = $0.7 < |\eta_{det}| < 1.5$, EC = $1.5 < |\eta_{det}| < 2.5$.

6.5.2 Cross section calculation

6.5.2.1 Unsmearing

In order to determine particle level cross sections, we unsmear the measured data jet multi-plicities. We use a special $Z+1$ jet PYTHIA MC sample by choosing PYTHIA 2-to-2 subpro-cesses 15 and 30 [1] with a parton p_T cut-off of 8 GeV and by applying vertex smearing. This sample only contains particle level jets (no detector simulation). We then apply the full data resolution smearing to the particle jet p_T as well as the data jet reco/ID efficiencies. Comparing the inclusive jet multiplicity for this MC sample with the one in data gives an idea of how well the MC describes the data (Figure 55). There is increasing disagreement at higher jet multi-plicities, since PYTHIA does not include higher order contributions at the hard scatter level. We correct for this discrepancy by taking the ratio between data and MC for each inclusive jet multiplicity (Figure 56) and then applying correction factors (per event) based on the absolute values of these ratios. After this additional step we again compare the inclusive jet multiplicity spectrum in MC with the one in data and find much better agreement (Figure 57). We use this corrected MC sample to derive the final unsmearing and jet reco/ID coefficients. Figure 58 - Figure 69 compare jet p_T and η distributions between the data and MC sample.

To calculate the coefficients we first take the inclusive jet multiplicity histogram for particle level jets with $p_T > 20$ GeV and $|\eta_{physics}| < 2.5$ and divide it by the inclusive jet multiplicity histogram for particle level jets with smeared $p_T > 20$ GeV and $|\eta_{physics}| < 2.5$ (plus applying jet

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[1] $f_i \bar{f}_i \rightarrow g Z^0$ and $f_i g \rightarrow f_i Z^0$

Jet multiplicity	Unsmearing and jet reco/ID coefficient
≥ 1	$1.10\ ^{+0.08}_{-0.06}$
≥ 2	$1.26\ ^{+0.18}_{-0.16}$
≥ 3	$1.50\ ^{+0.25}_{-0.24}$
≥ 4	$1.90\ ^{+0.52}_{-0.39}$
≥ 5	$4.00\ ^{+3.42}_{-1.13}$

TABLE X

UNSMEARING AND JET RECO/ID COEFFICIENTS WITH SYSTEMATIC
UNCERTAINTY DUE TO RESOLUTION AND JET RECO/ID EFFICIENCY.

reco/ID efficiencies). The absolute values of these ratios yield the unsmearing and jet reco/ID coefficients which can be applied as multiplicative factors to the measured jet multiplicities in data. Figure 70 shows the numerator and denominator jet multiplicity histograms, as well as the ratio when applying jet smearing and jet reco/ID efficiencies in the denominator. For comparison Figure 71 shows the same distributions without applying jet reco/ID efficiencies, i.e. applying only jet smearing.

We use the statistical error of each unsmearing and jet reco/ID coefficient as a statistical error to the final cross sections (see Chapter 6.6.7). Table X summarizes all coefficients.
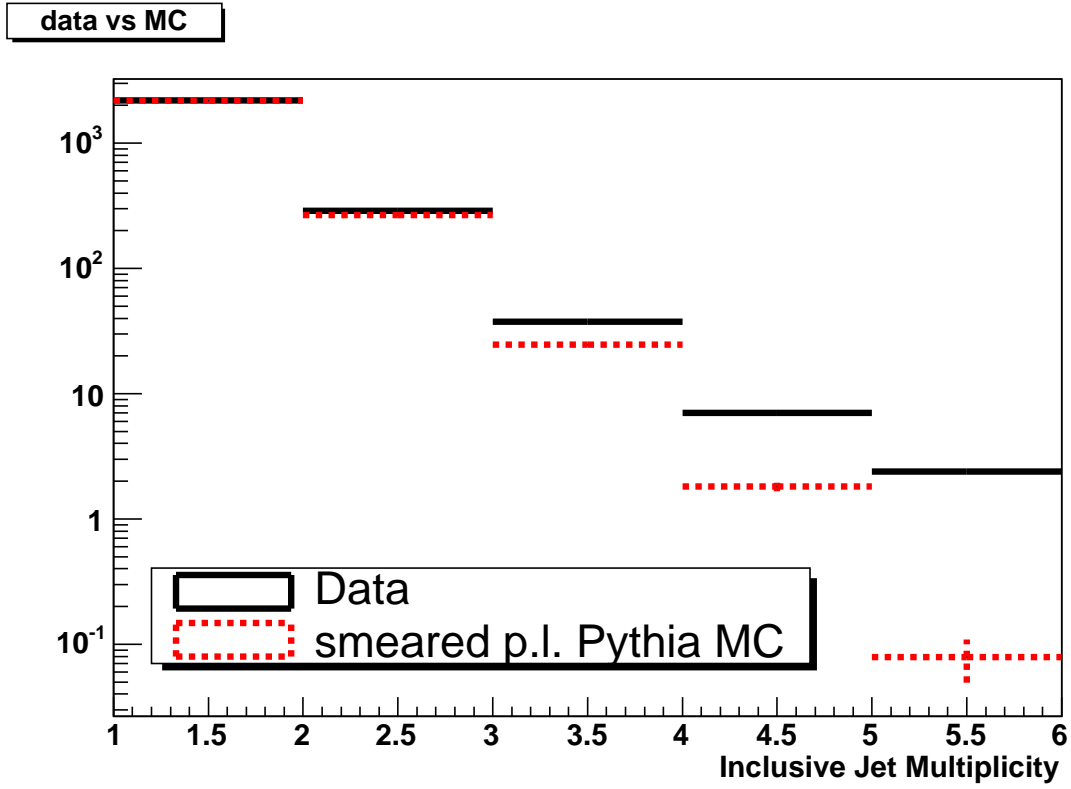
Figure 55. Comparing inclusive jet multiplicities between data and particle level MC (applying data resolution smearing and data jet reco/ID efficiencies). The distributions are normalized with respect to the first bin.
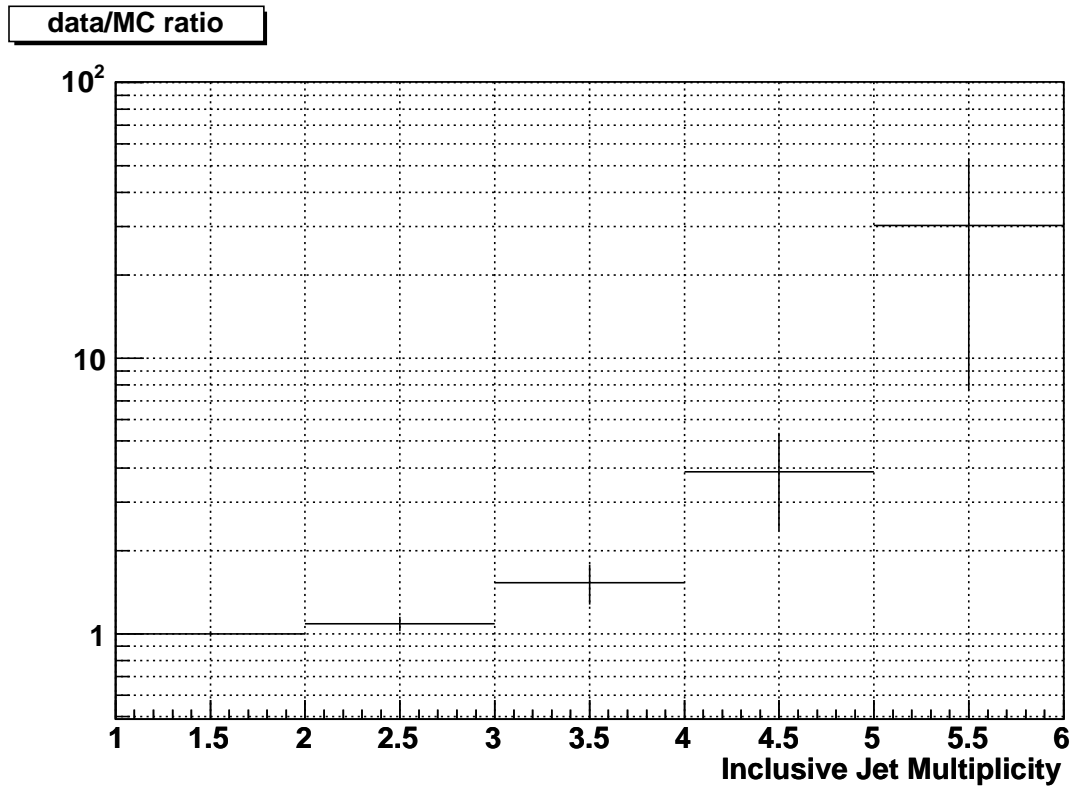
Figure 56. Ratio of MC (with smearing and jet reco/ID efficiencies) inclusive jet multiplicities and data inclusive jet multiplicities.
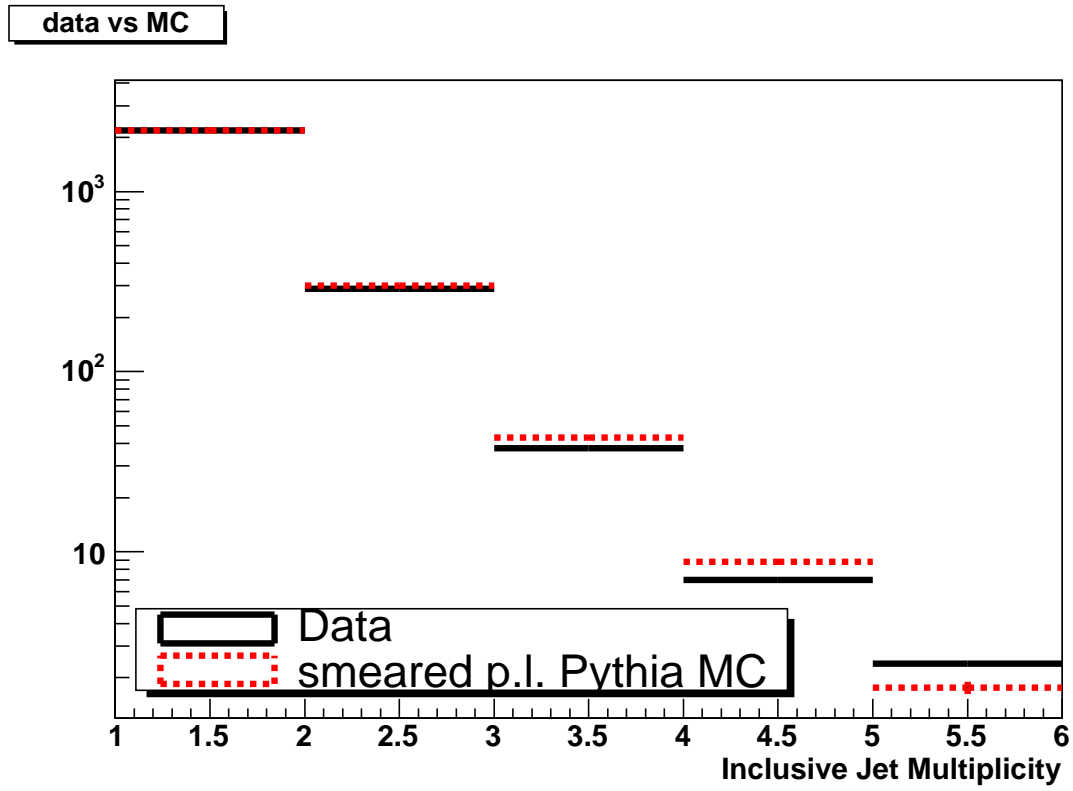
Figure 57. Comparing inclusive jet multiplicities between data and particle level MC (after applying correction factors). The distributions are normalized with respect to the first bin.
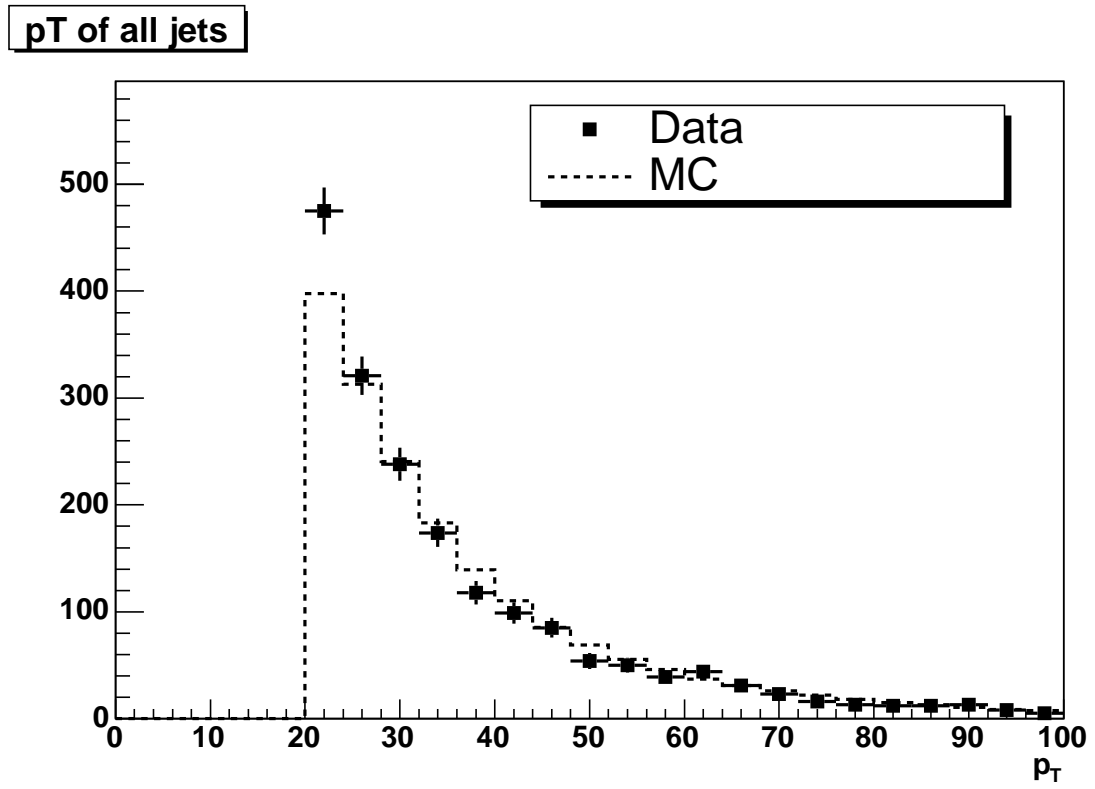
Figure 58. Comparing jet p_T for all jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied).
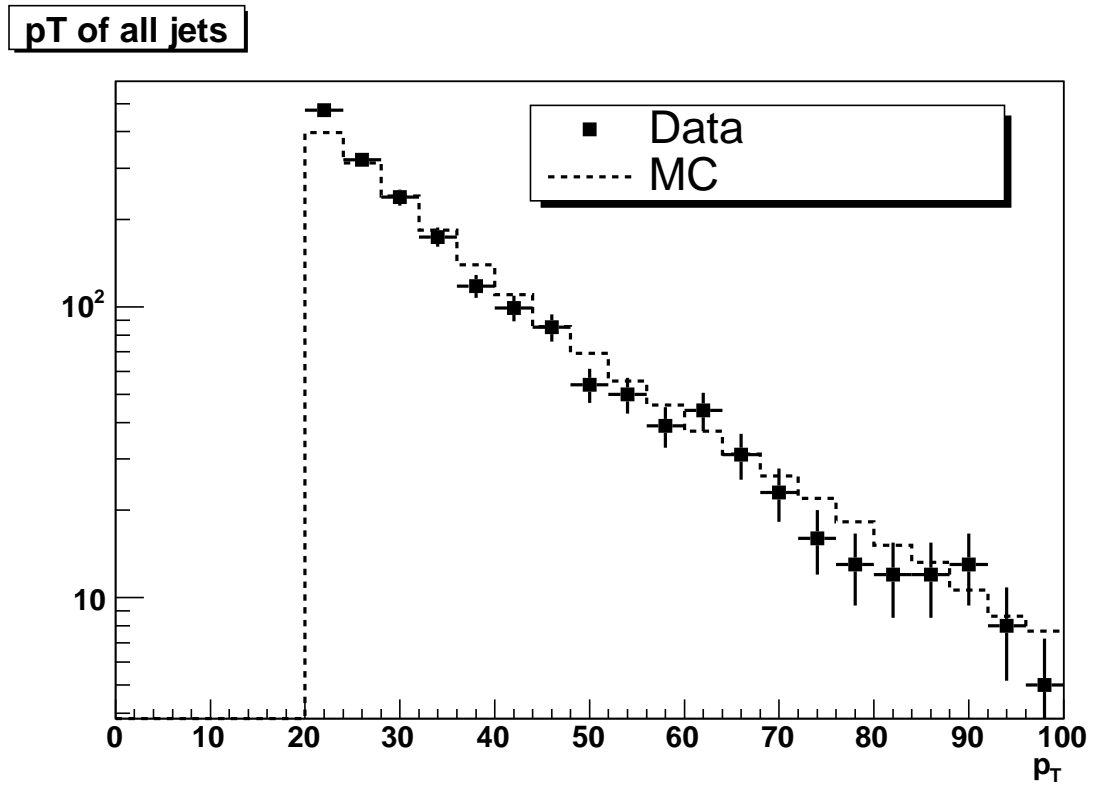
Figure 59. Comparing jet p_T for all jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied).
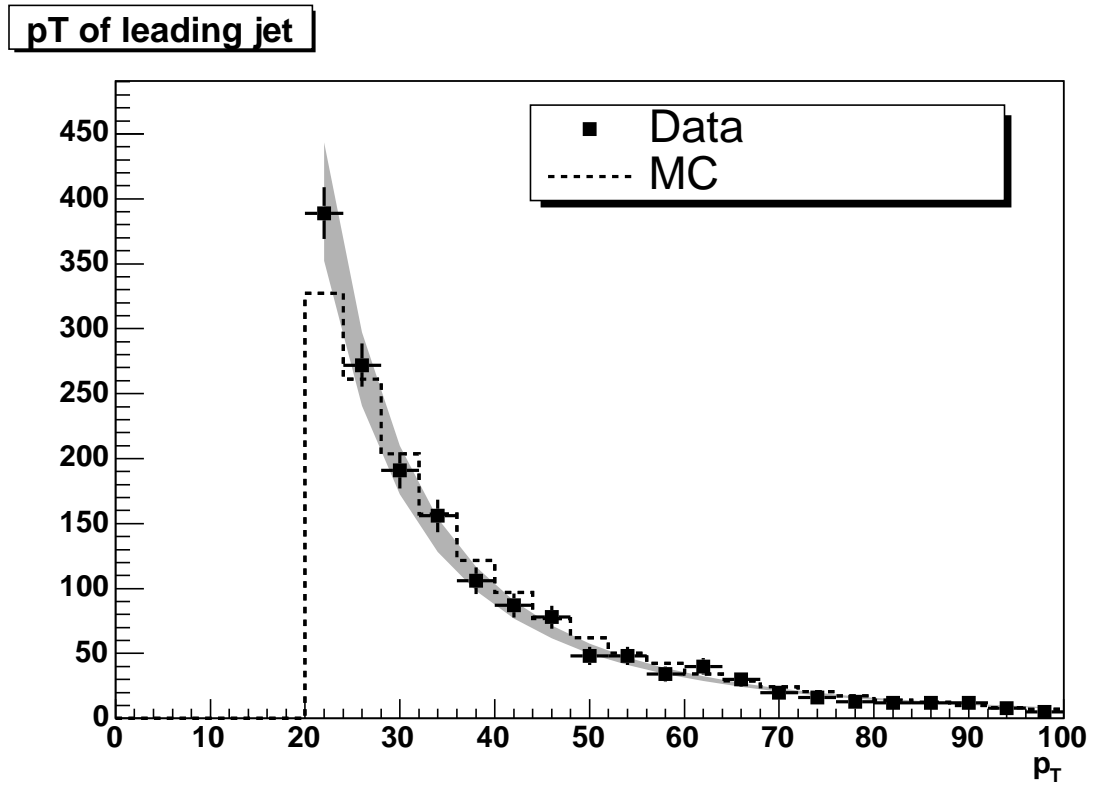
Figure 60. Comparing jet p_T for leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.13. The gray band shows the uncertainty due to the jet energy scale.
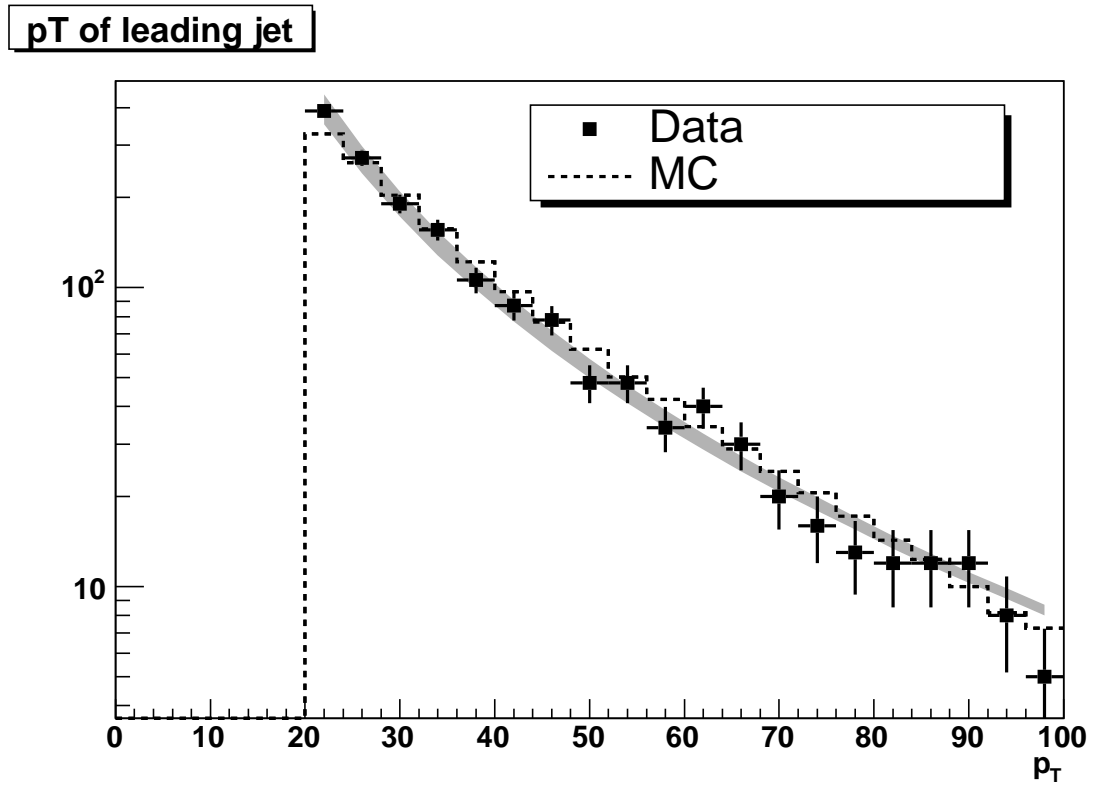
pT of leading jet

Figure 61. Comparing jet p_T for leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.13. The gray band shows the uncertainty due to the jet energy scale.
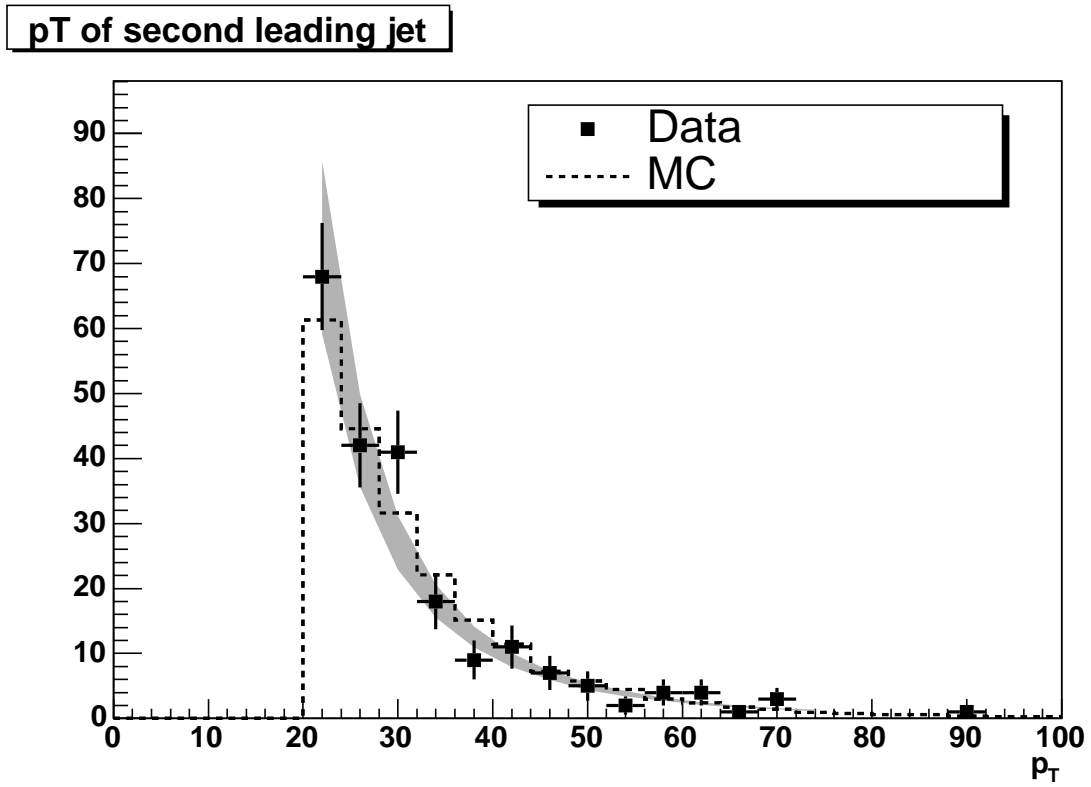
Figure 62. Comparing jet p_T for second leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.56. The gray band shows the uncertainty due to the jet energy scale.
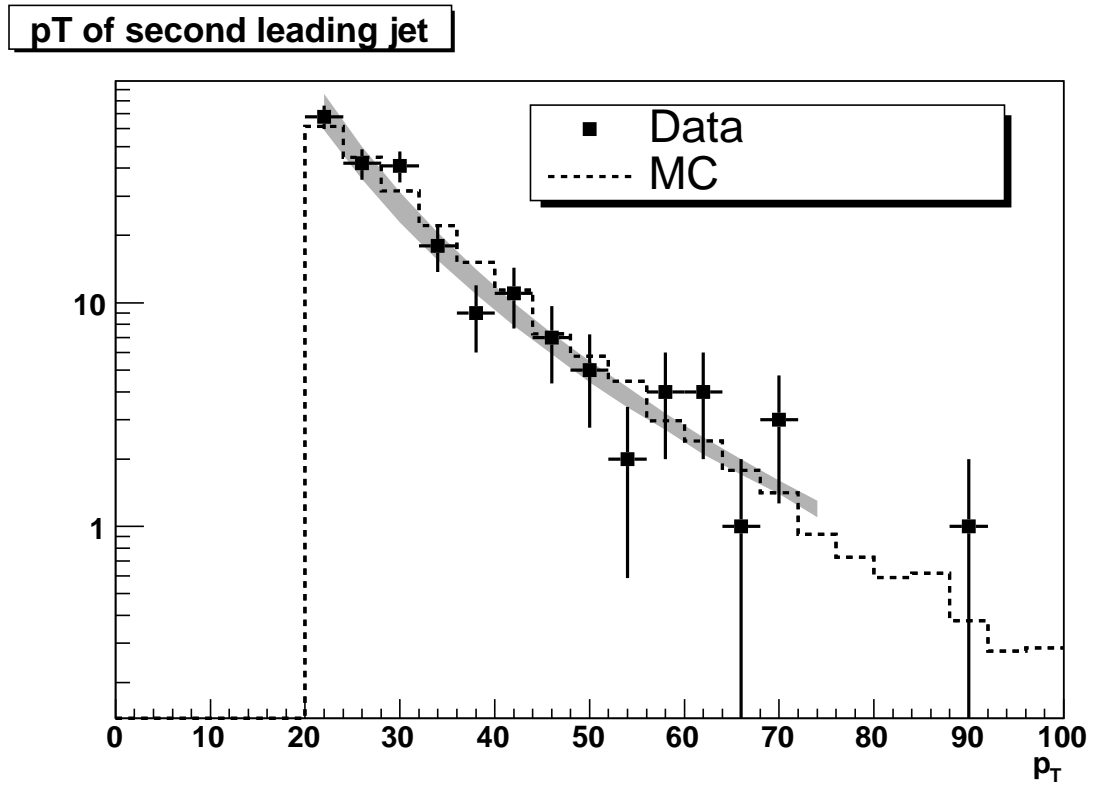
Figure 63. Comparing jet p_T for second leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.56. The gray band shows the uncertainty due to the jet energy scale.

pT of third leading jet
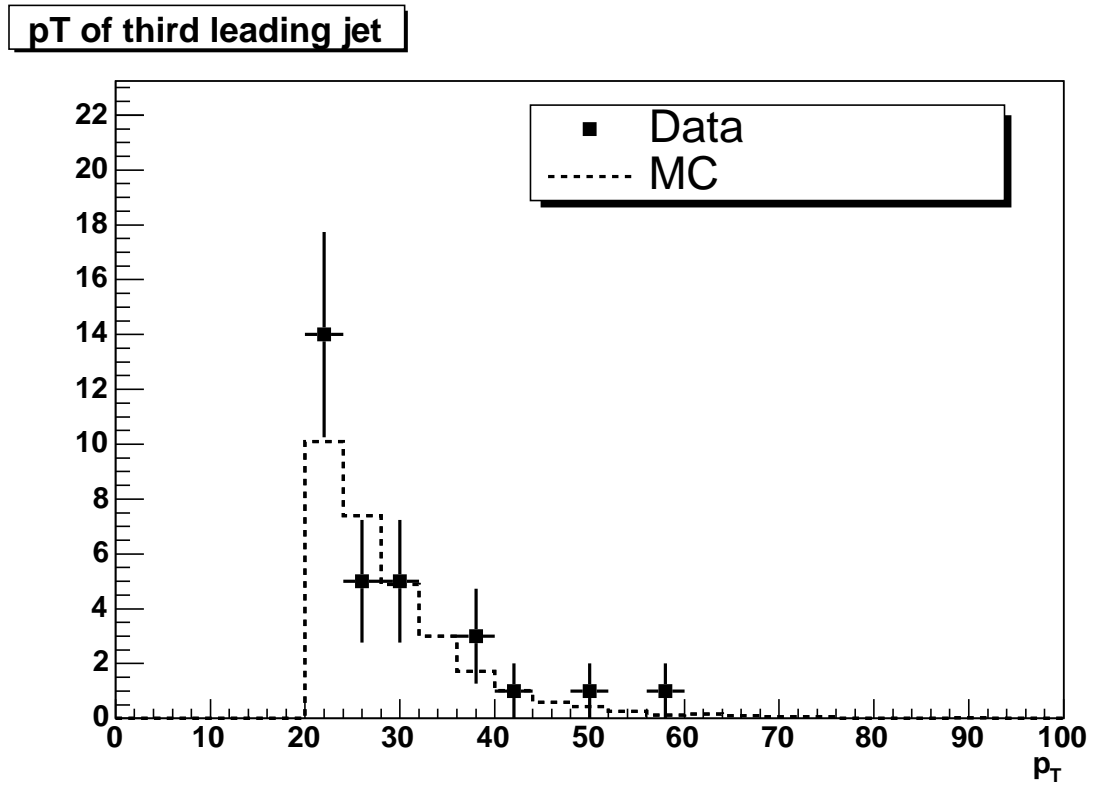
Figure 64. Comparing jet p_T for third leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.57.
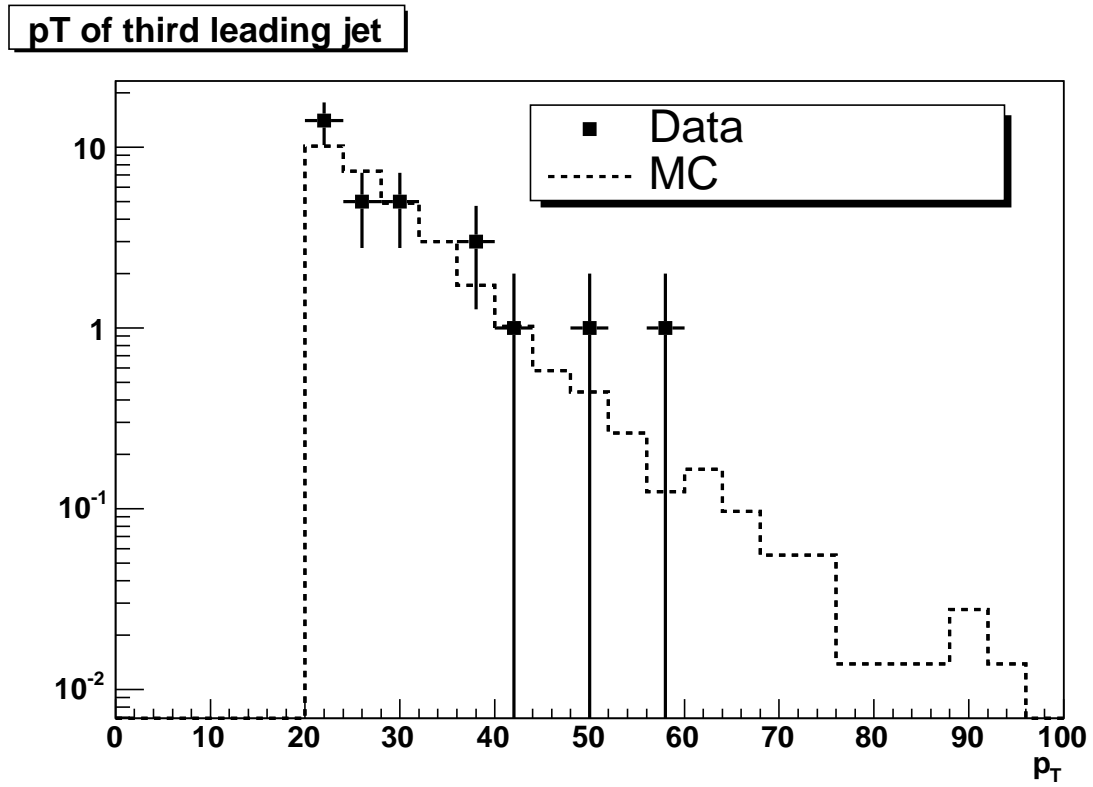
Figure 65. Comparing jet p_T for third leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.57.
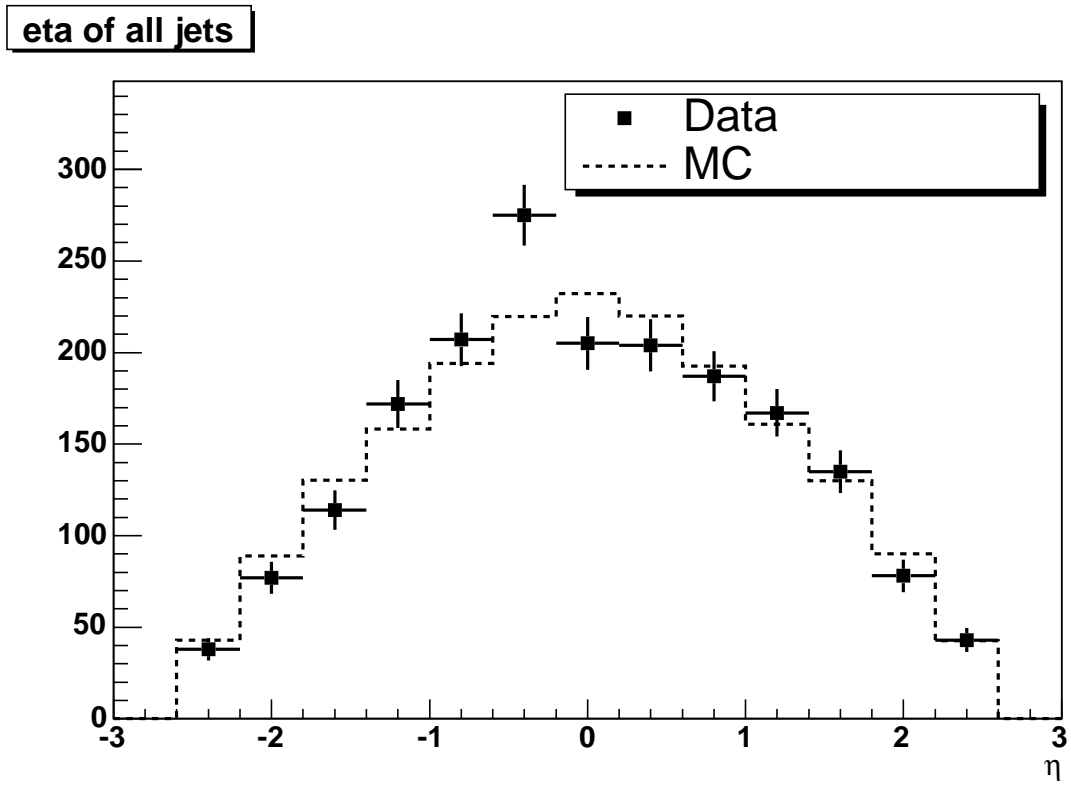
Figure 66. Comparing jet η for all jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied).
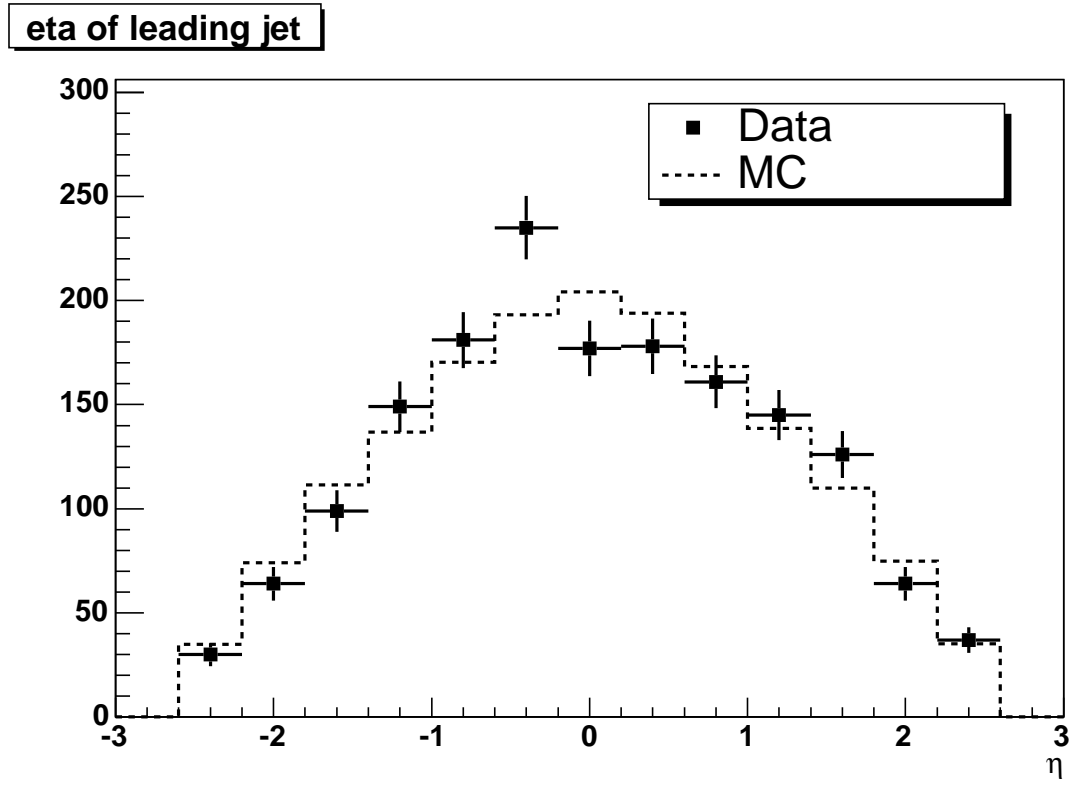
Figure 67. Comparing jet η for leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.70.
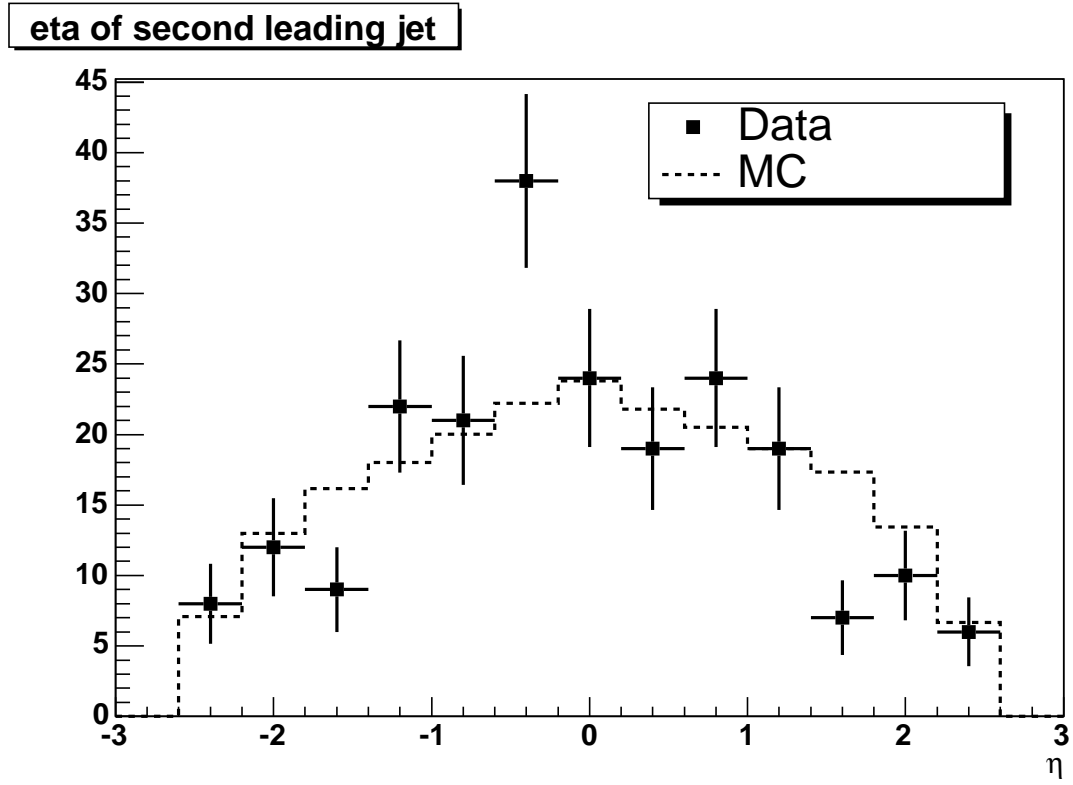
Figure 68. Comparing jet η for second leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.30.
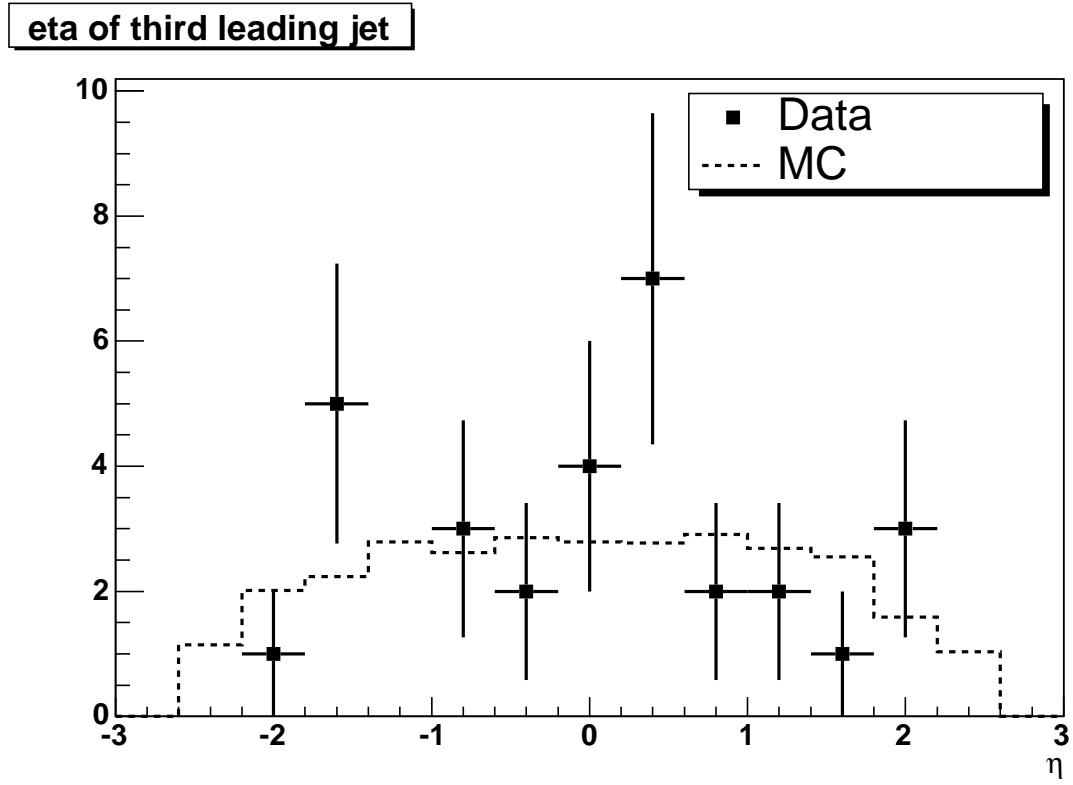
Figure 69. Comparing jet η for third leading jets between data and particle level MC (with data resolution smearing and jet reco/ID efficiencies applied). Kolmogorov-Smirnov Probability = 0.93.
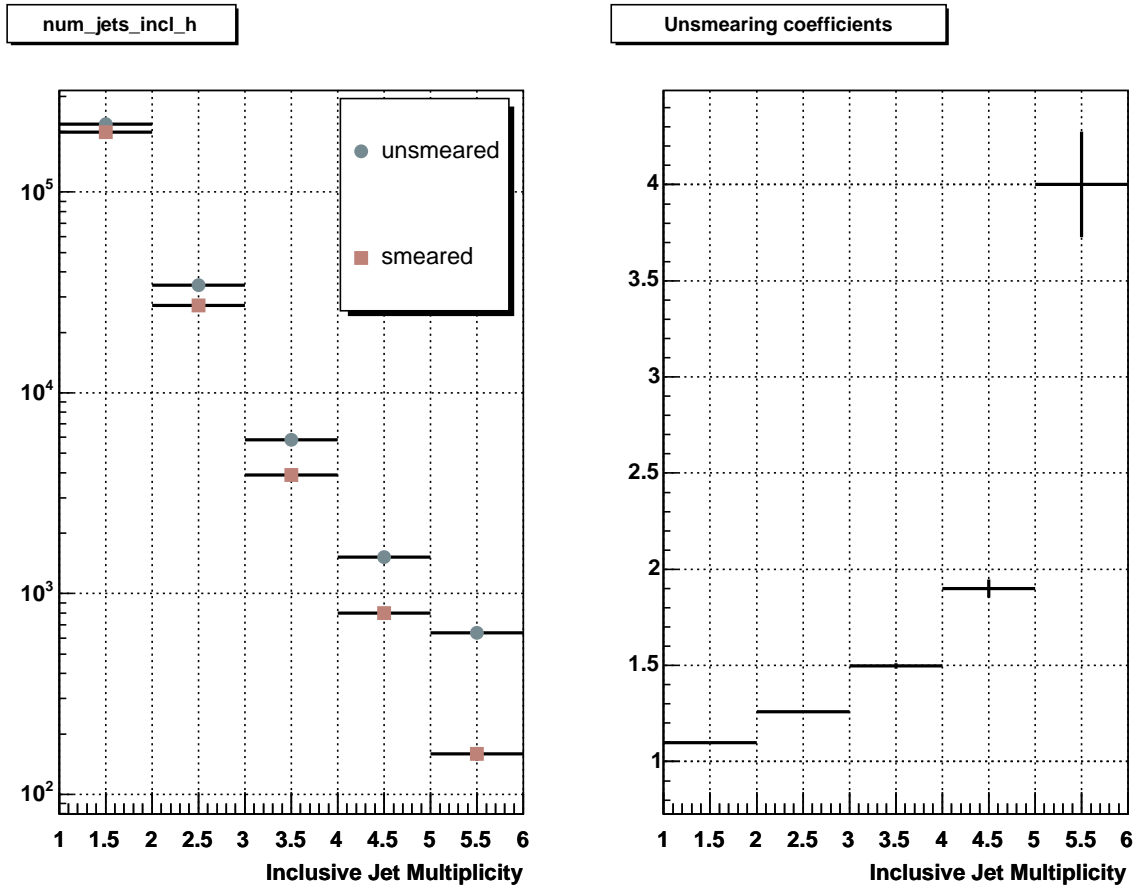
Figure 70. Unsmearing and jet reco/ID particle jet multiplicities (left) and coefficients (right).
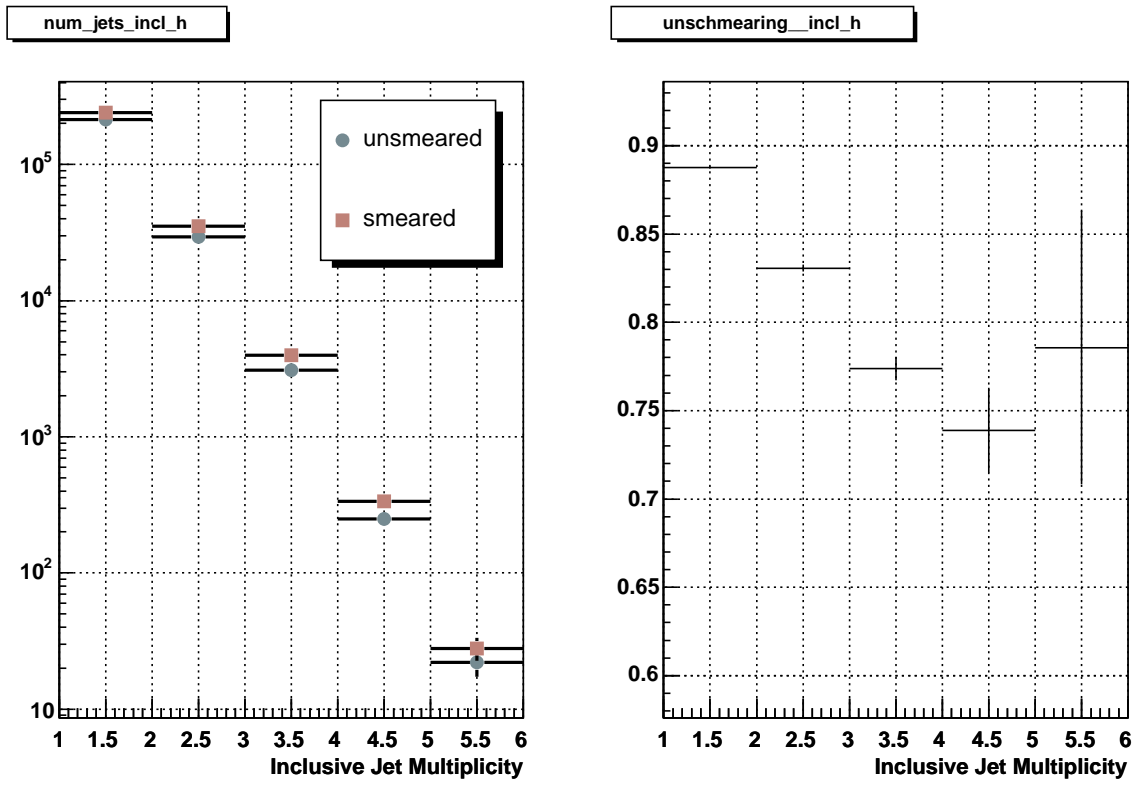
Figure 71. Unsmearing jet multiplicities (left) and coefficients (right) without applying jet reco/ID efficiencies.

6.5.2.2   <u>Electron-Jet-Overlap Correction</u>

Using the tag-and-probe method outlined in Chapter 6.4.1.2, we plot the ΔR distribution between probe tracks and reconstructed jets that pass all jet quality cuts except for the electron-jet-overlap cut in data and MC (Figure 72 and Figure 73).

We see an excess of entries at ΔR values of 0 and π due to fake jets (i.e. originated from the electron energy deposits) which survived the jet quality cuts. Therefore we reject all jets that are near the two electrons within ΔR=0.4. Figure 74 shows the same distribution as in Figure 72 after adding the electron-jet-overlap cut. For comparison Figure 75 shows the ΔR between generated electrons and partons in data and MC.

An additional correction needs to be derived in order to account for the real jets that are removed by the electron-jet-overlap cut. Using the same MC sample as for the unsmearing studies (see Chapter 6.5.2.1) we estimate the correction factors due to the electron-jet-overlap by taking the ratio of the inclusive parton multiplicity distribution for all partons with $p_T > 20$ GeV and $|\eta| <2.5$ and the inclusive parton multiplicity distribution for partons that are outside of the ΔR cone with respect to the electrons from the Z.

We derive correction factors using ΔR cones of size 0.4 and 0.7 and take the middle value as the final correction factors. This is done in order to account for the position resolution between partons and calorimeter jets (see Figure 76). Additionally we apply a linear fit to the final values in order to compensate for statistical fluctuations.

Table XI summarizes the electron-jet-overlap correction factors for different jet multiplicity
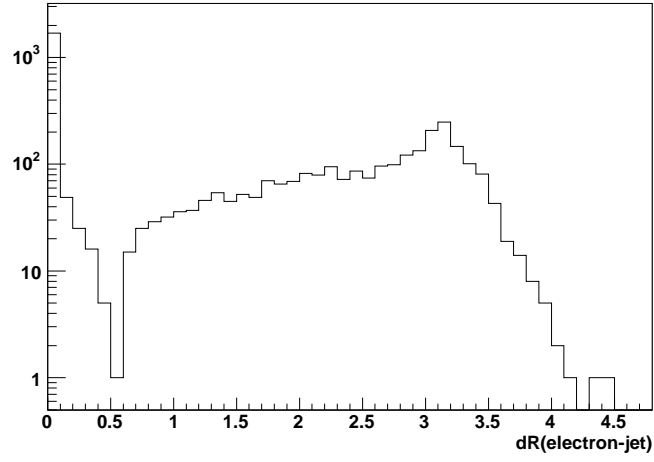
Figure 72. ΔR between probe-tracks and good jets in data (without electron-jet-overlap cut).

samples. We apply these corrections as multiplicative factors to the measured jet multiplicities

in data.
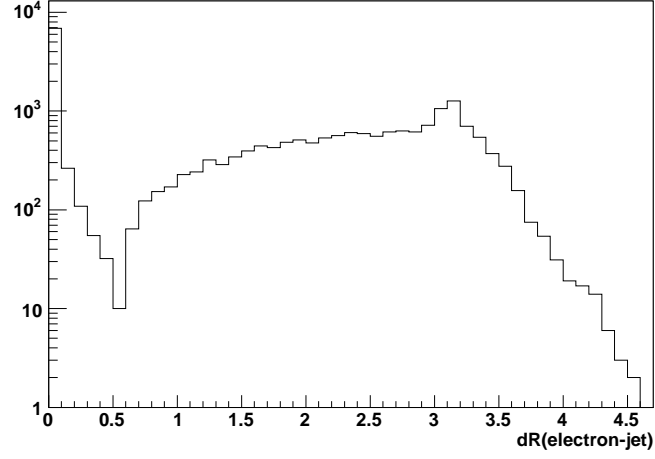
Figure 73. ΔR between probe-tracks and good jets using PYTHIA MC (without electron-jet-overlap cut).

Jet Multiplicity	Electron-Jet-Overlap Coefficient
≥ 1	1.059 ± 0.028
≥ 2	1.075 ± 0.041
≥ 3	1.092 ± 0.054
≥ 4	1.109 ± 0.067
≥ 5	1.125 ± 0.077

TABLE XI

ELECTRON-JET-OVERLAP COEFFICIENTS WITH SYSTEMATIC UNCERTAINTIES.
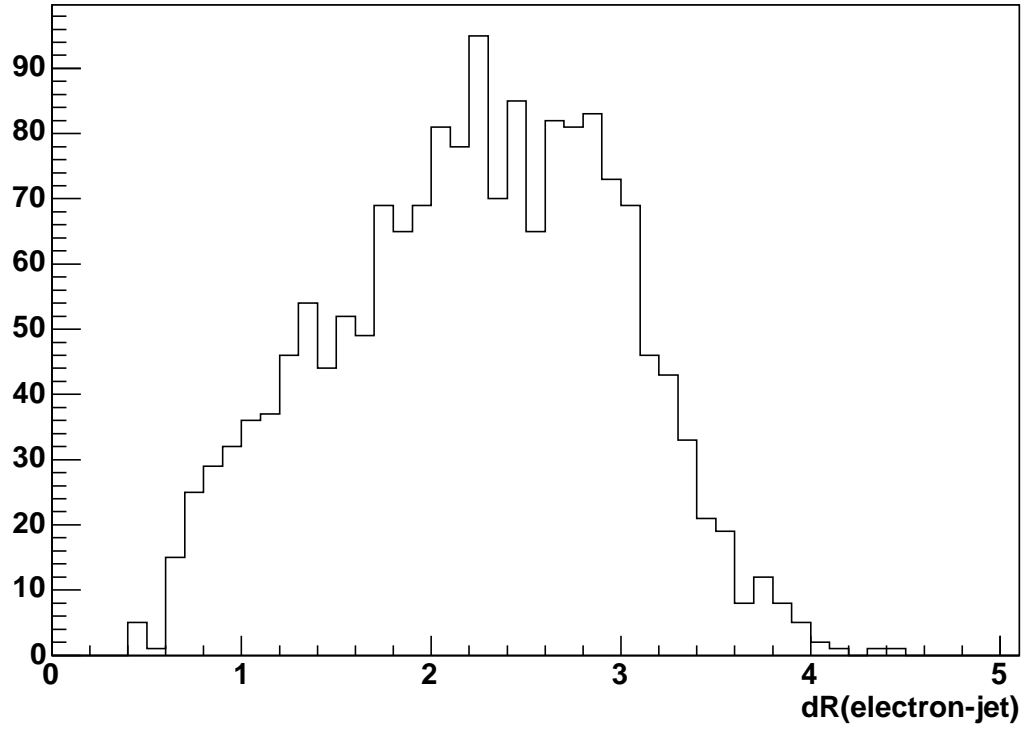
Figure 74. ΔR between probe-tracks and good jets in data (after the electron-jet-overlap cut was applied).
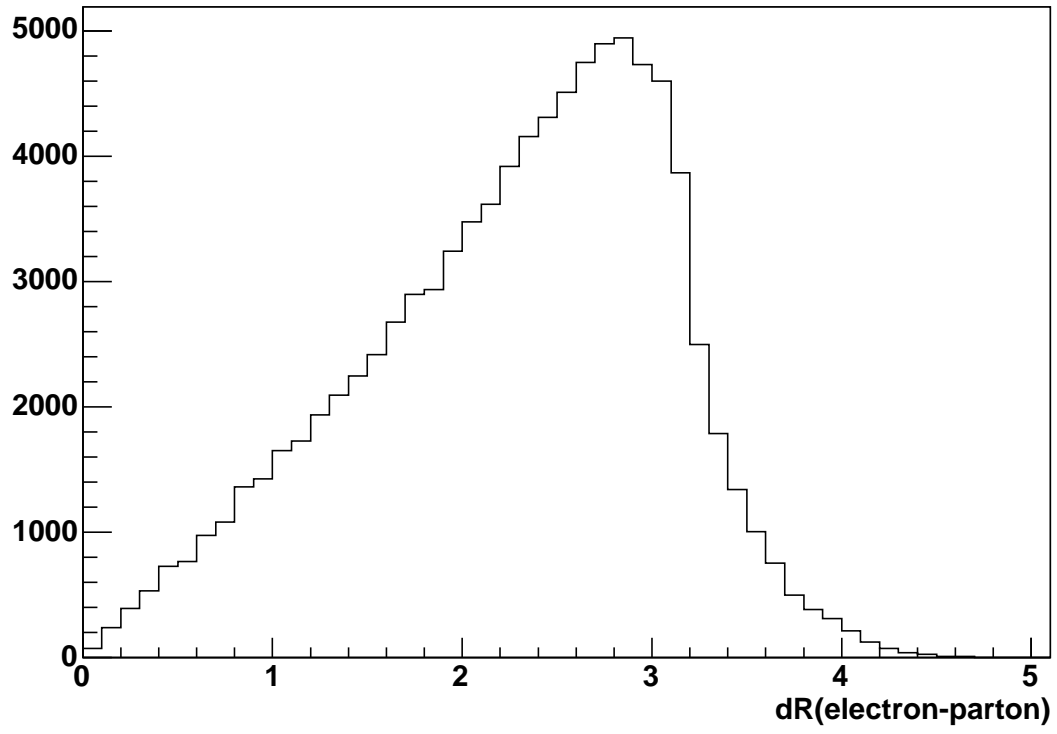
Figure 75. ΔR between generated electrons ($p_T > 25$ GeV, $|\eta| < 1.1$) and partons ($p_T > 20$ GeV, $|\eta| < 2.5$).
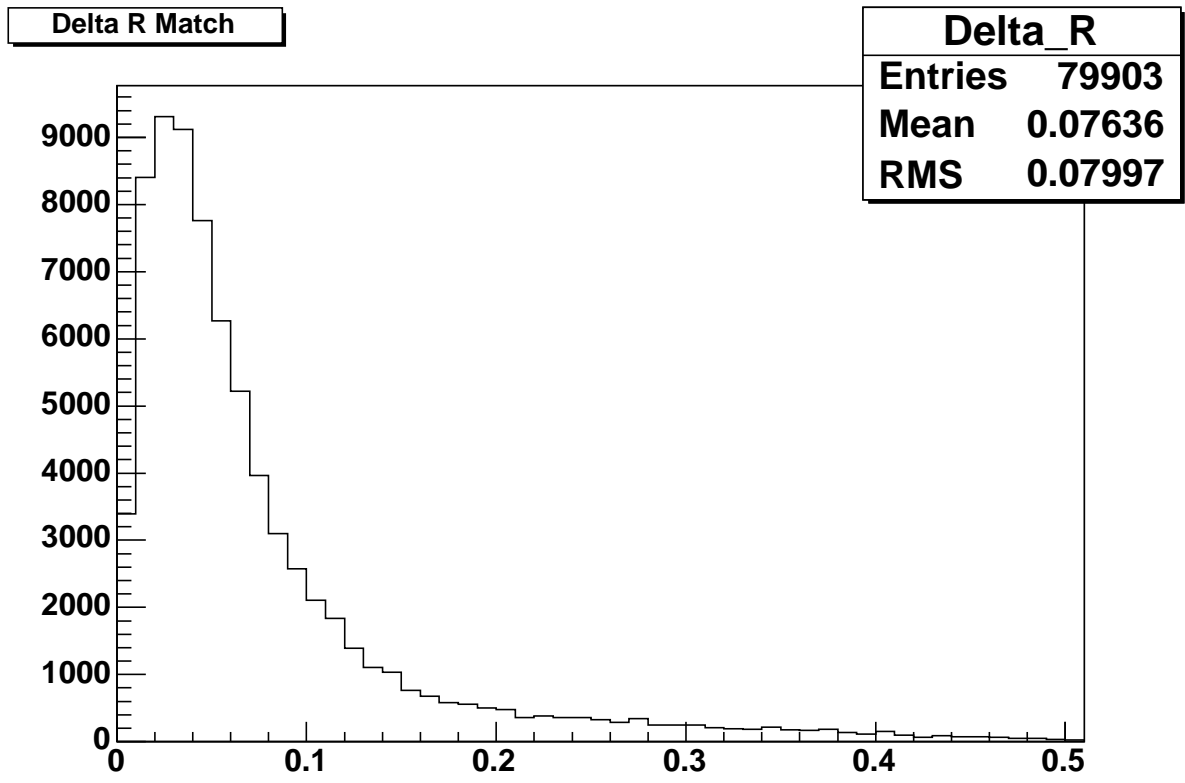
Figure 76. ΔR between partons and matched calorimeter jets ($p_T > 20$ GeV, $|\eta| <$2.5).

Jet Multiplicity	Total number of entries	Signal	Background
≥ 1	2,625.2	2,550.7 (52.5)	74.6
≥ 2	404.5	392.0 (8.1)	12.5
≥ 3	64.7	61.6 (1.3)	3.1
≥ 4	14.7	14.7 (-)	0
≥ 5	10.8	10.8 (-)	0

TABLE XII

NUMBER OF SIGNAL EVENTS (DRELL-YAN IN PARENTHESIS) AND NUMBER OF BACKGROUND EVENTS (QCD) FOR DIFFERENT JET MULTIPLICITIES. NUMBERS ARE CORRECTED FOR TRIGGER, EM AND TRACKING INEFFICIENCIES (AFTER APPLYING THE UNSMEARING, JET RECO/ID AND ELECTRON-JET-OVERLAP CORRECTIONS).

6.5.2.3   Cross sections

Figure 77 through Figure 81, show the diem invariant mass distributions for jet multiplicities ≥ 1 to ≥ 5 which we use to extract the number of signal and background events for the cross section calculation (corrected for trigger, EM and tracking inefficiencies). For jet multiplicities of ≥ 1 and ≥ 2, we follow the same technique as outlined in Chapter 6.4.2. For jet multiplicities of ≥ 3 we use sidebands to estimate the background. For higher jet multiplicities there is not enough statistics to estimate any background.

Table XII summarizes the number of signal and background events for each jet multiplicity. The fully corrected and unsmeared cross sections versus jet multiplicities (with jet $p_T > 20$ GeV, $|\eta| < 2.5$) are shown in Figure 82 with statistical errors.
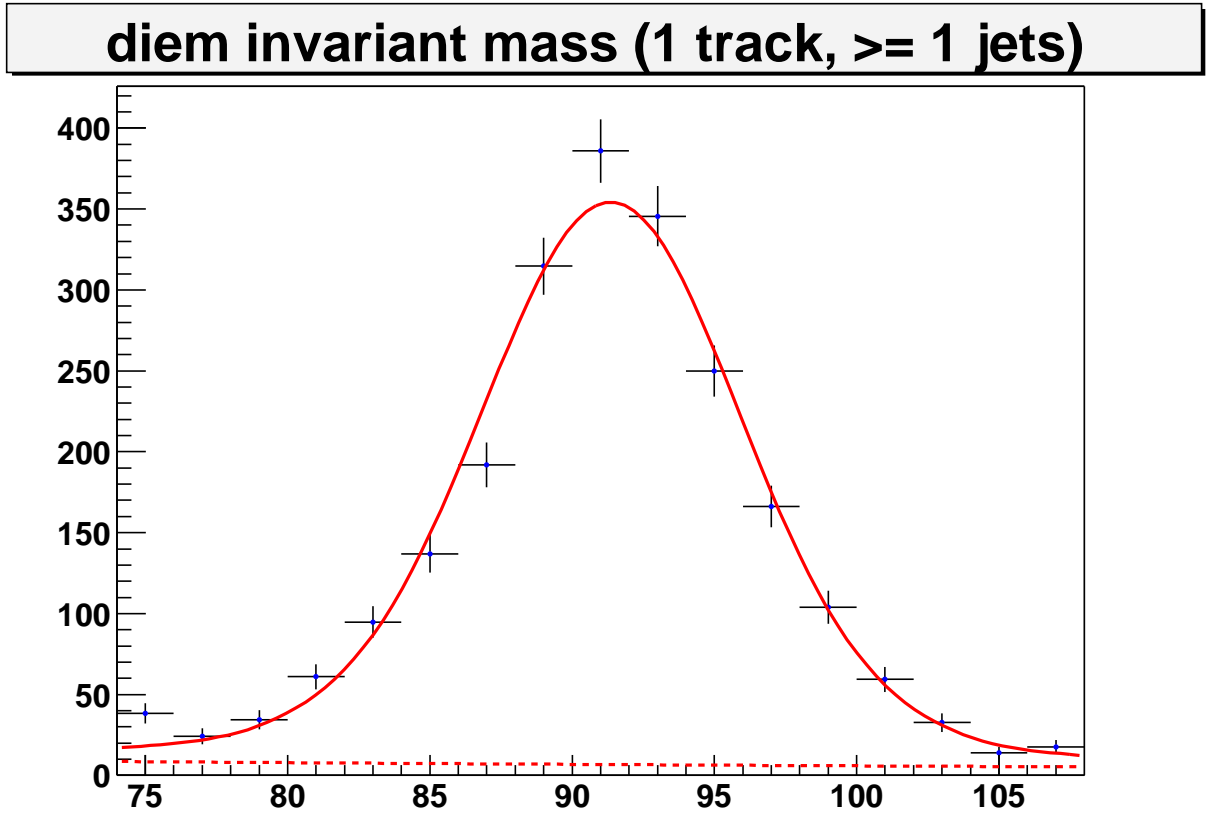
Figure 77. Diem invariant mass distribution for the $Z/\gamma^* \to e^+e^- + \geq 1$ jet sample. The solid line shows a Gaussian plus Breit-Wigner fit to the Z peak. The dashed line shows an exponential fit to the QCD and Drell-Yan contribution.
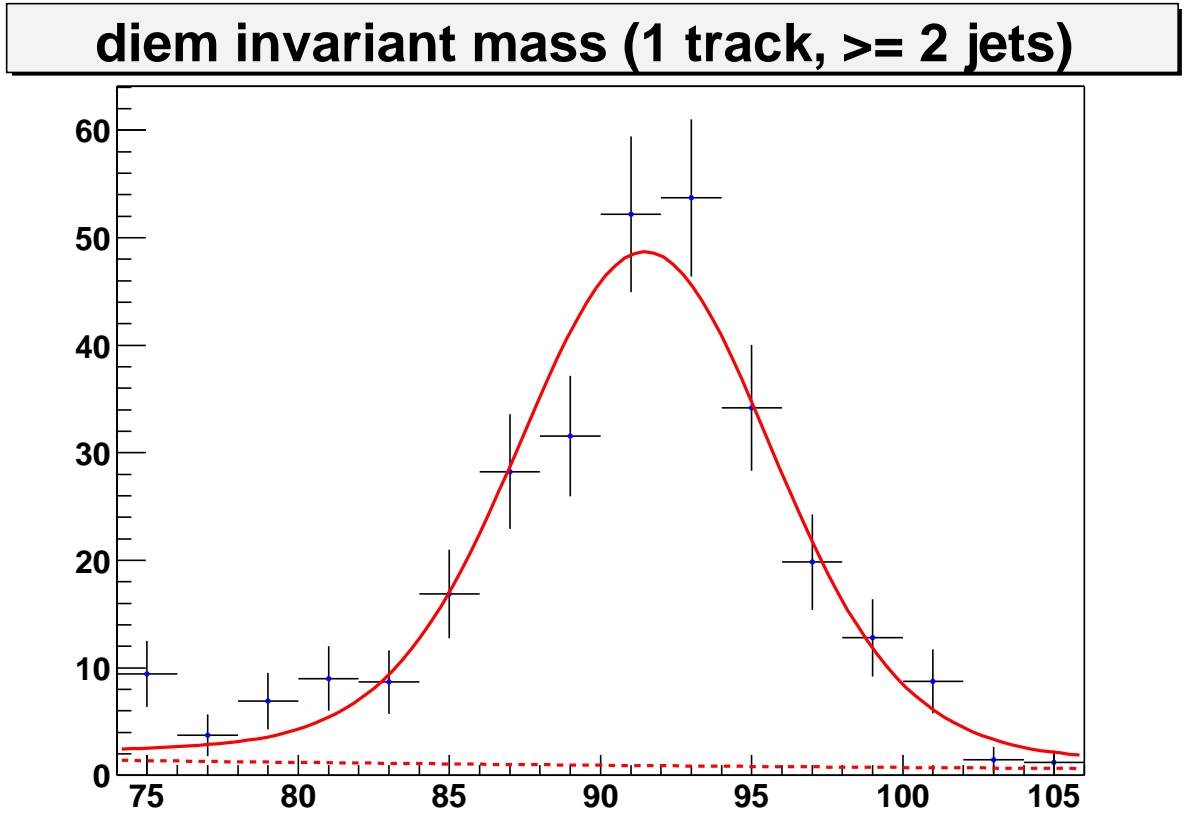
Figure 78. Diem invariant mass distribution for the $Z/\gamma^* \to e^+e^- + \geq 2$ jet sample. The solid line shows a Gaussian plus Breit-Wigner fit to the Z peak. The dashed line shows an exponential fit to the QCD and Drell-Yan contribution.
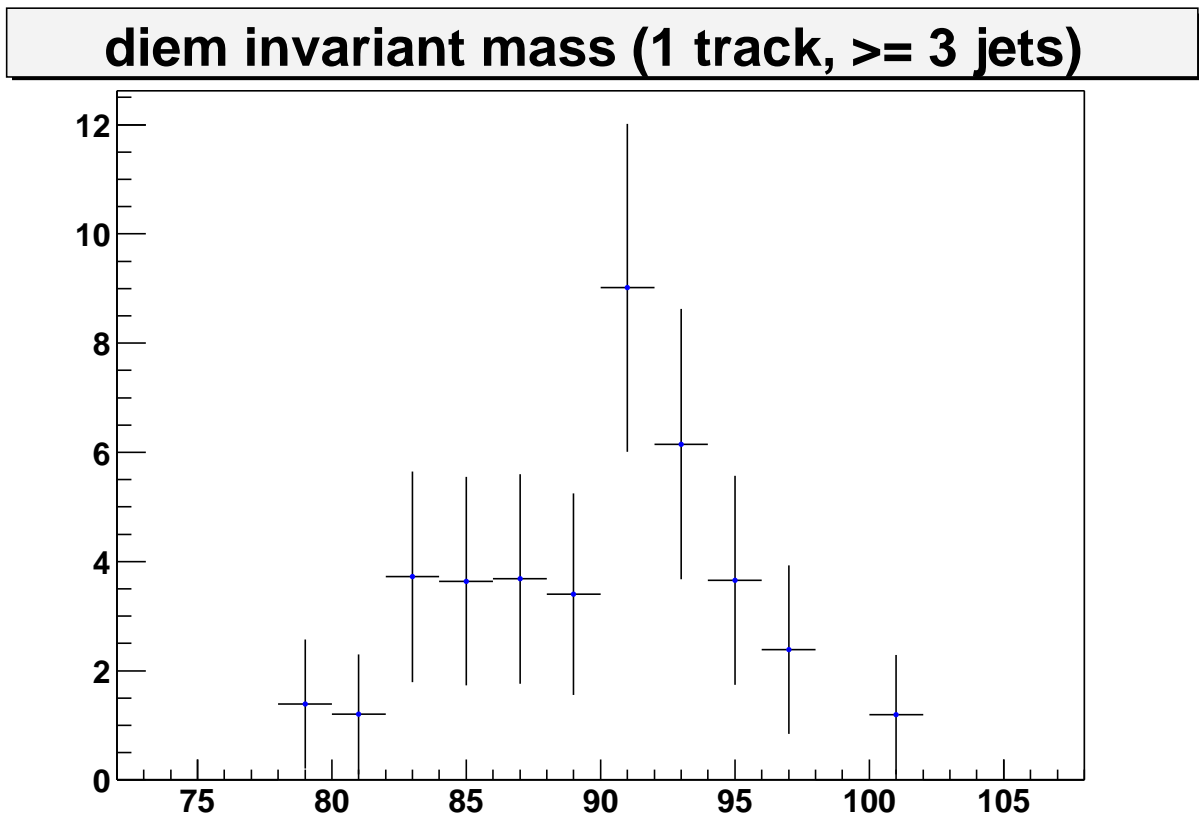
Figure 79. Diem invariant mass distribution for the $Z/\gamma^* \rightarrow e^+e^- + \geq 3$ jet sample.
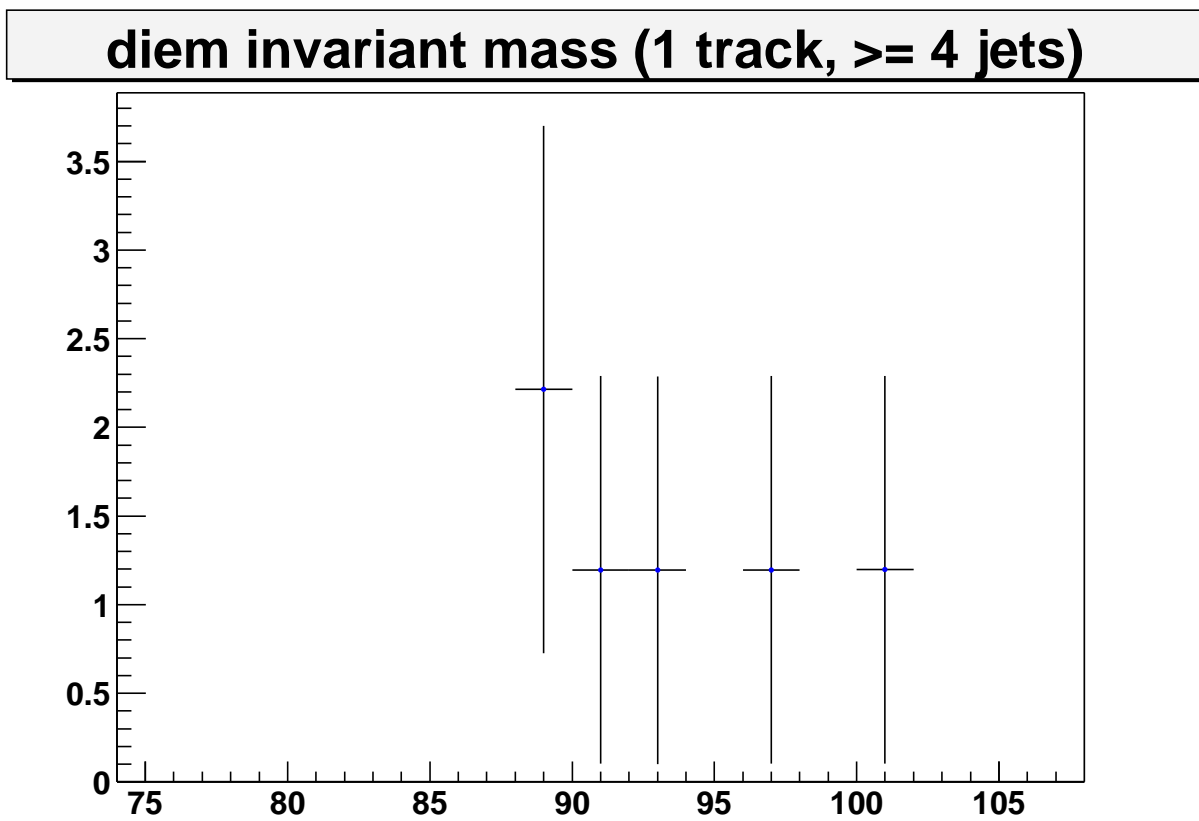
Figure 80. Diem invariant mass distribution for the $Z/\gamma^* \to e^+ e^- + \geq 4$ jet sample.
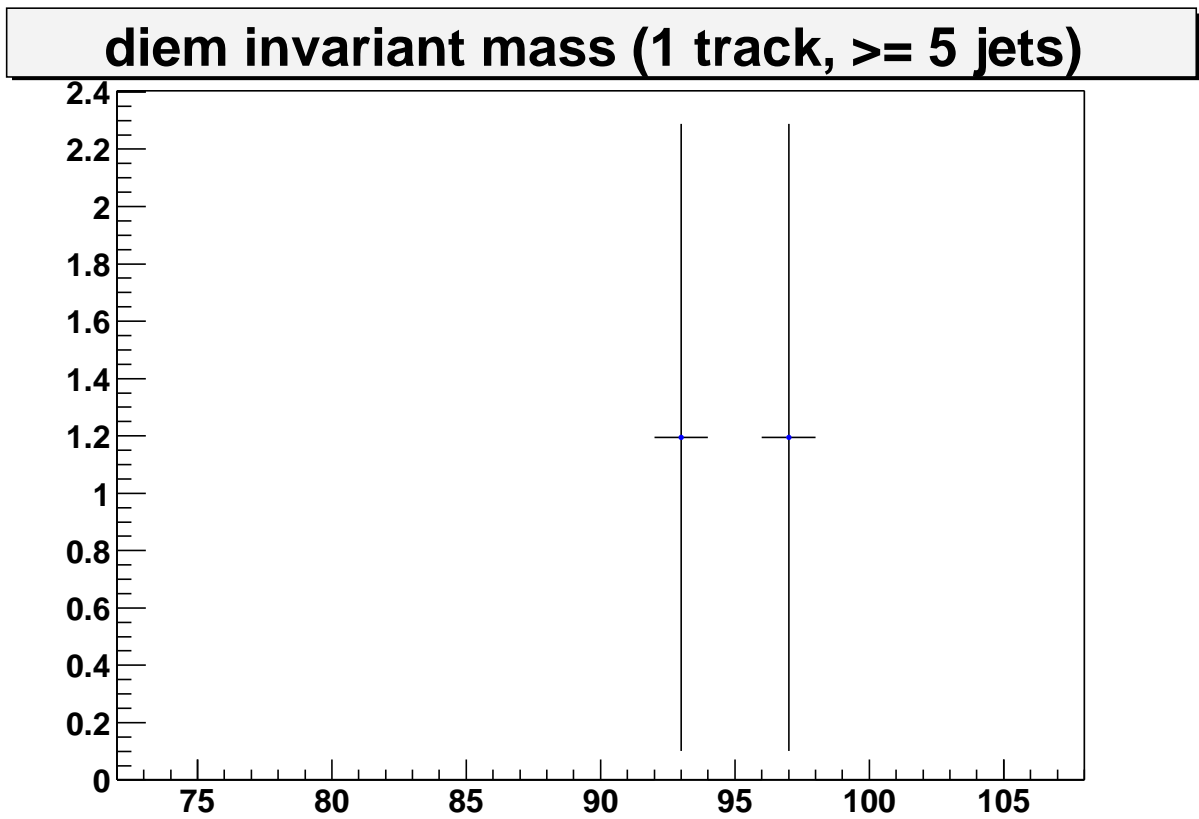
Figure 81. Diem invariant mass distribution for the $Z/\gamma^* \to e^+e^- + \geq 5$ jet sample.
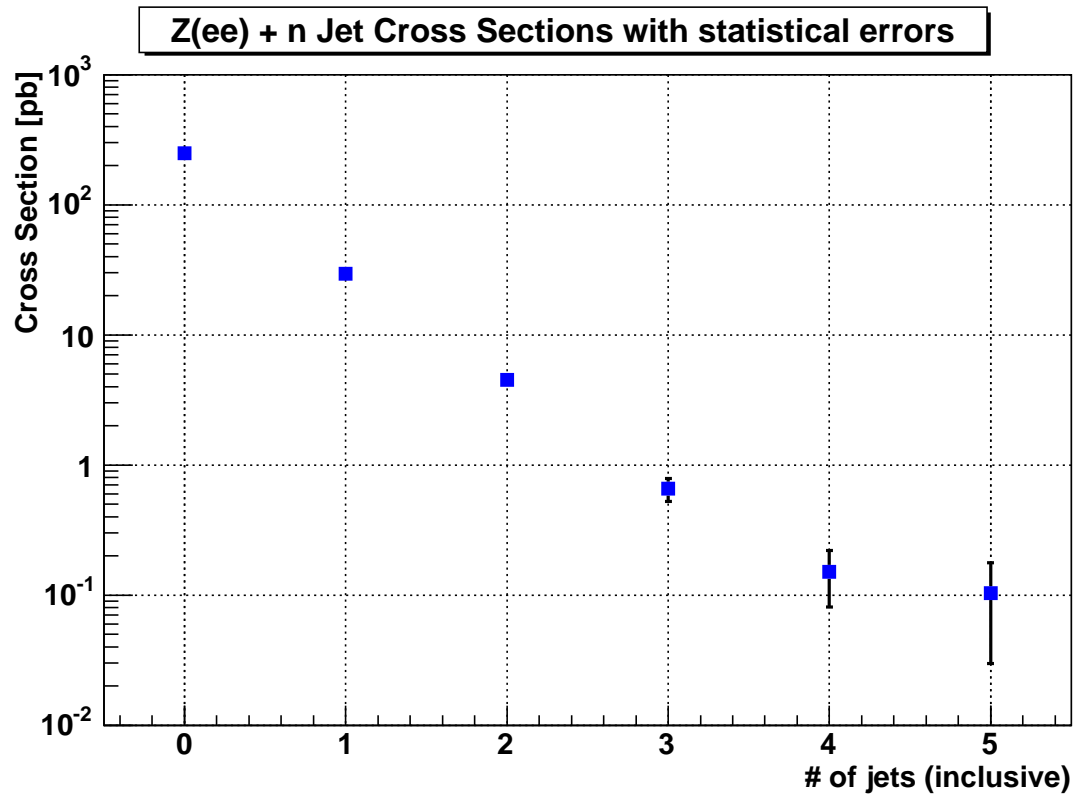
Figure 82. Cross sections for inclusive jet multiplicities with statistical errors.

Jet multiplicity	Cross Section	JES Errors
≥ 1	29.6 pb	±2.9 pb
≥ 2	4.50 pb	±0.83 pb
≥ 3	0.655 pb	±0.185 pb
≥ 4	0.151 pb	±0.057 pb
≥ 5	0.1035 pb	±0.0520 pb

TABLE XIII

FINAL CROSS SECTIONS WITH JES ERRORS.

6.6   Systematics

6.6.1   Jet Energy Scale Systematic Error

We estimate the error due to the jet energy scale (version 5.3) by moving the energy scale correction up and down by 1σ (combined systematic and statistical JES uncertainty) and subsequently rederiving the diem invariant mass histograms (corrected for trigger, EM reco/ID, and EM-Track matching inefficiencies) to get the number of corrected signal events for different jet multiplicities. We then recalculate the cross sections to estimate the JES error. Figure 83 shows the effect of the JES error on the corrected jet multiplicity distribution.

We fit the percentage errors for each jet multiplicity linearly to get a smooth curve and to be independent from statistical fluctuations. The final JES error is the maximum of the actual data error and the fit error. Table XIII summarizes the JES errors. The JES errors are the dominant errors in this analysis.
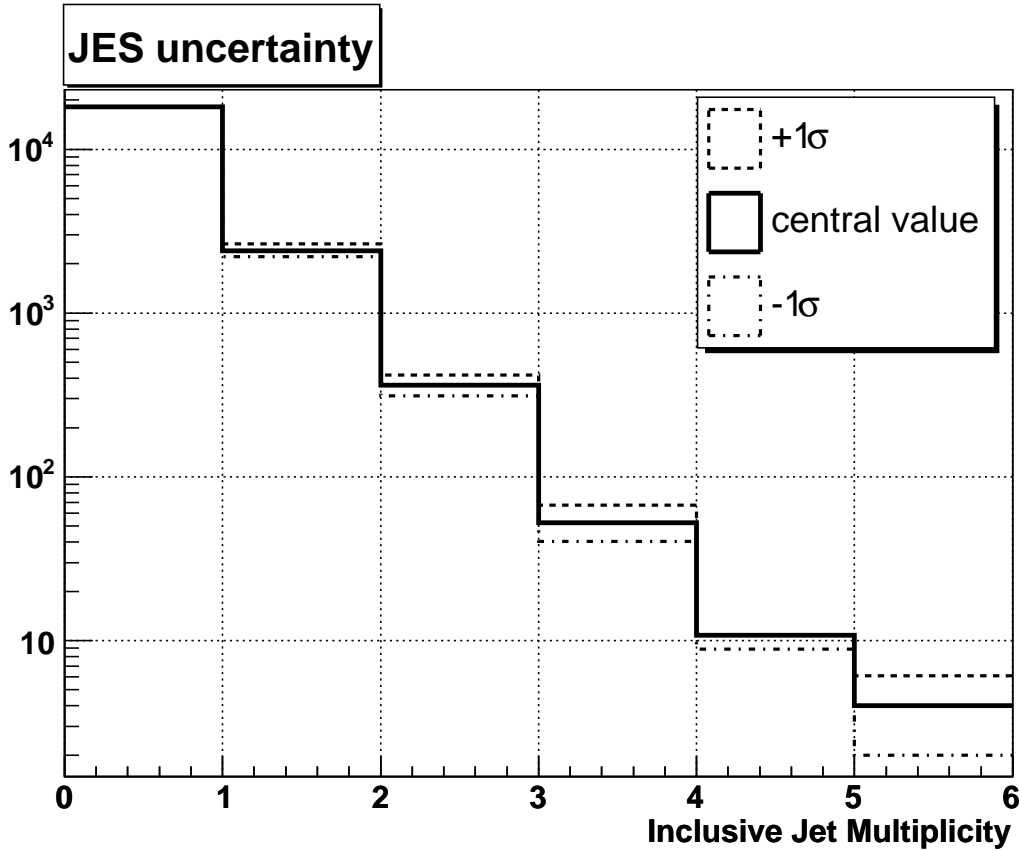
Figure 83. $\pm 1\sigma$ fluctuation of the jet energy scale (JES 5.3)

6.6.2 Systematic Error of Cross Section Unfolding

- A detailed description of the jet reco/ID efficiency errors can be found in (45). Figure 84, Figure 85 and Figure 86 show the jet reco/ID efficiencies with error bands. The errors are due to the statistical uncertainty of the scale factor and straight efficiency, the missing E_T cut, and differences between CKKW and PYTHIA MC generators. To estimate the jet reco/ID uncertainty we rederive the unsmearing and jet reco/ID correction factors using the upper and lower error bands of the jet reco/ID efficiencies.

  Figure 87 shows the scale factor used in this analysis overlaid with the average scale factor determined by the Top group. Both curves agree within the error bands.

  As a cross check we perform a closure test where we compare the "efficiency" of finding a recoiling jet as a function of $Z\ p_T$ in data and particle level MC (Figure 88). Both the data and MC distributions have a jet p_T cut of 8 GeV applied. In addition, the MC particle jets are smeared with the data jet energy resolution. We also apply the data jet reco/ID efficiencies (by dropping jets) to the MC sample. We find good agreement between the two distributions within errors.

  Table XIV summarizes the jet reco/ID errors.

- The parameterization of the jet resolution is based on JES 5.0 with T42 applied (see Chapter 6.1.2). We need to account for the difference between the JES 5.0 and 5.3 parameterizations. It has been shown (see Figure 89) that there is a change of approximately 5% between JES 5.1 and 5.3 (46). A conservative error of 10% is therefore assigned to account for the jet resolution uncertainty.
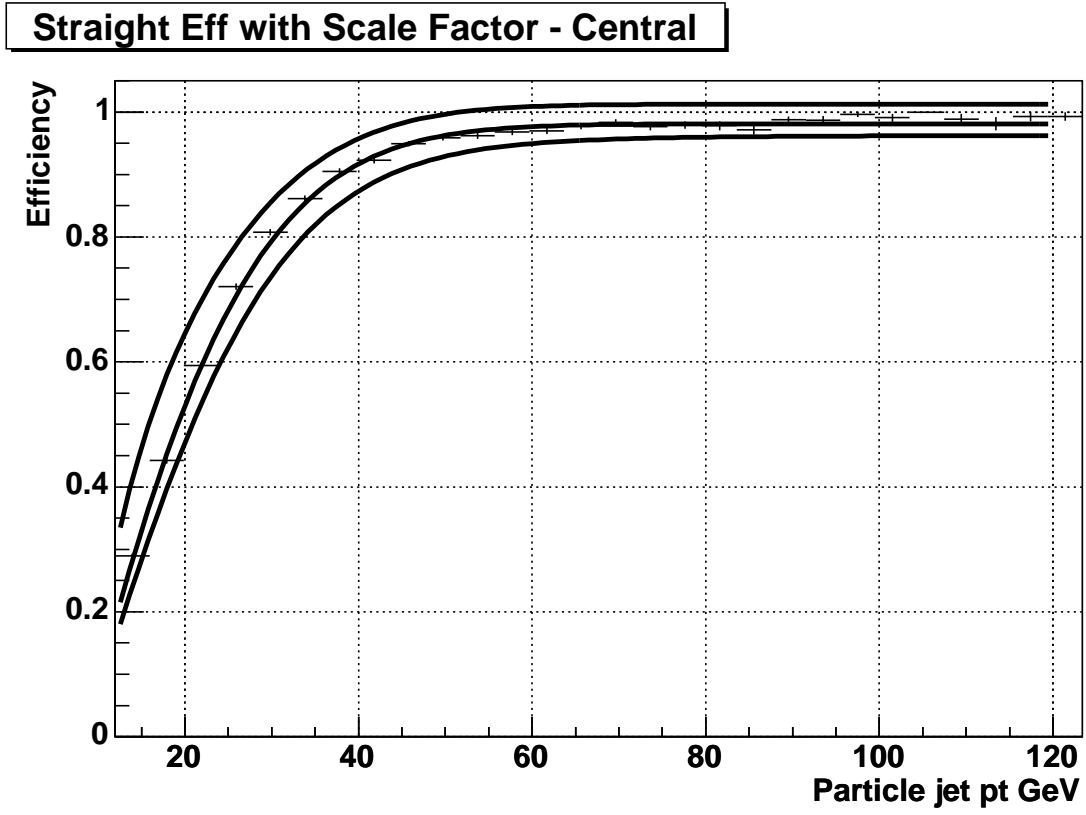
Figure 84. Jet reco/ID efficiencies with errors plotted versus particle jet p_T smeared with data energy resolution (central).
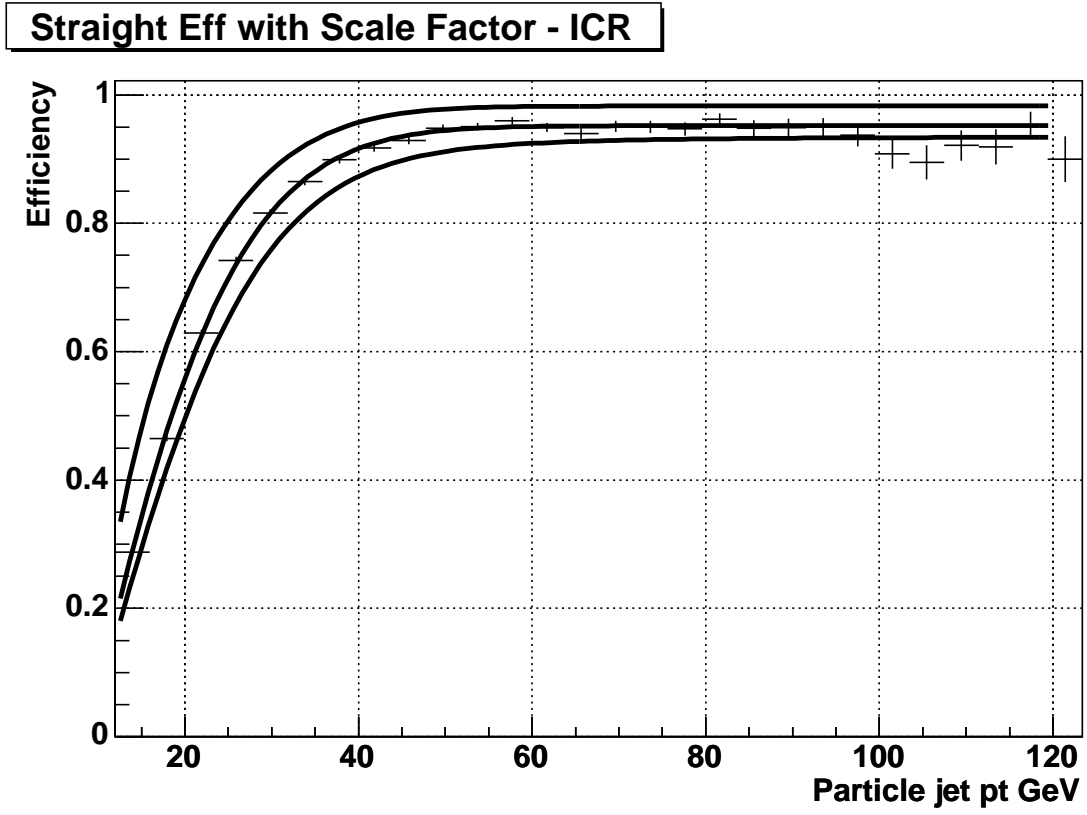
Figure 85. Jet reco/ID efficiencies with errors plotted versus particle jet p_T smeared with data energy resolution (ICR).
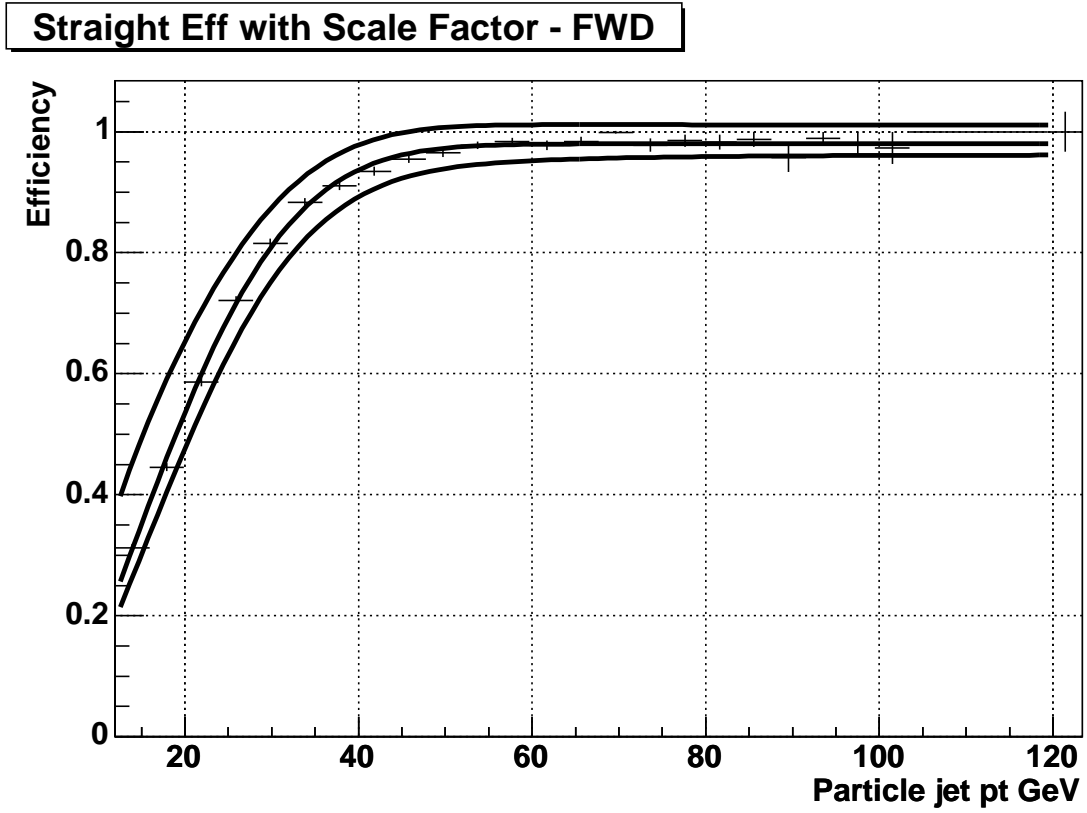
Figure 86. Jet reco/ID efficiencies with errors plotted versus particle jet p_T smeared with data energy resolution (forward).
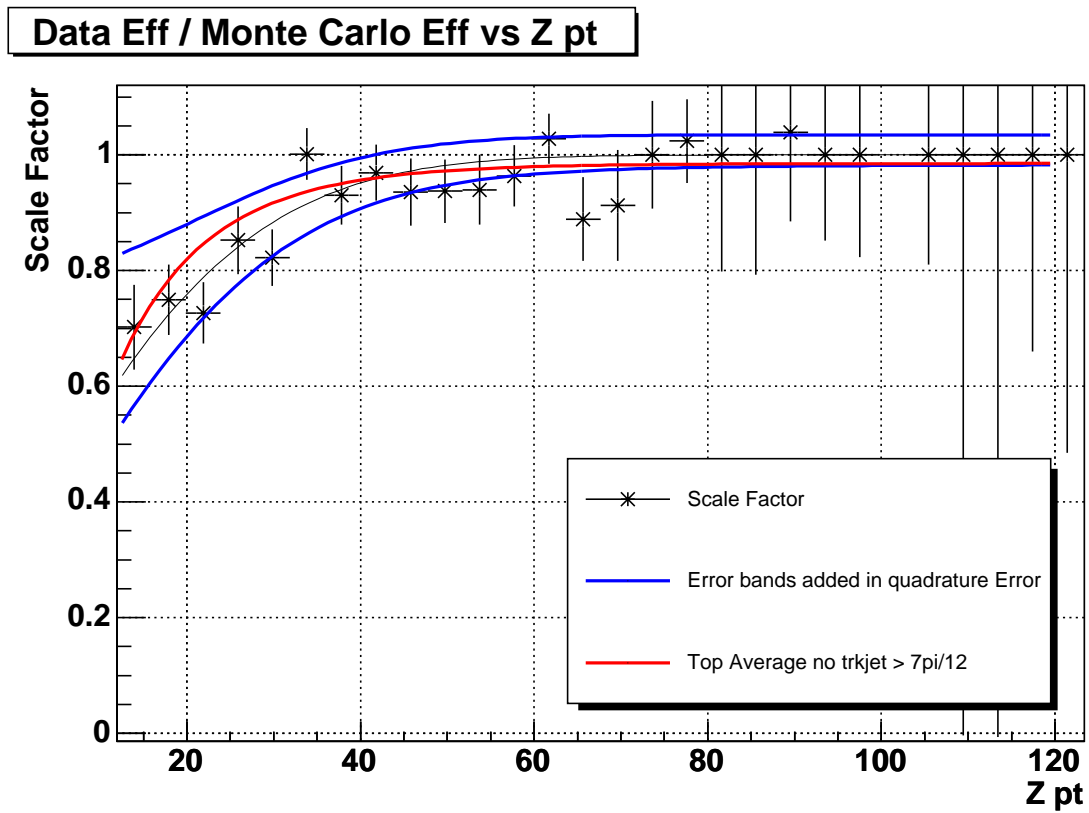
Figure 87. Comparing scale factors between the Top group and this analysis. Equivalent techniques were used in both cases.

Jet Reconst Eff Data
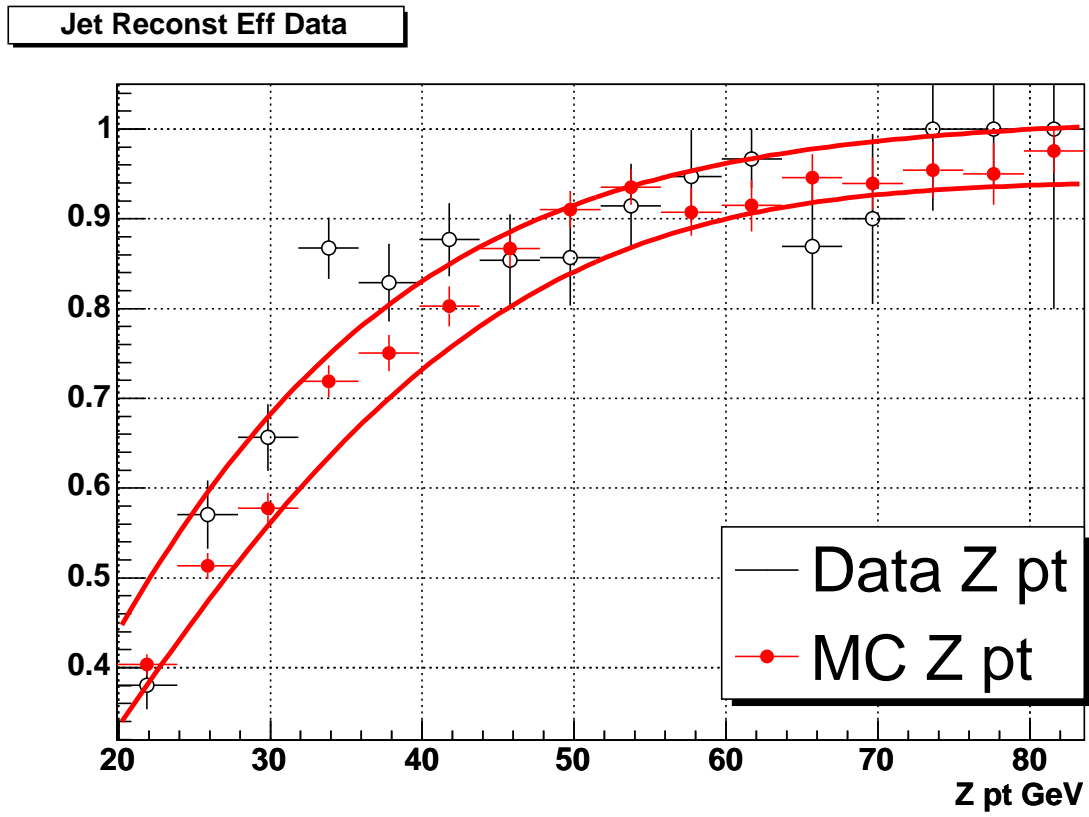
Figure 88. Comparing "efficiency" of finding a recoiling jet as a function of Z p_T in data and MC.

Jet multiplicity	Cross Section	Jet Reco/ID Errors
≥ 1	29.6 pb	$^{+2.2}_{-1.6}$pb
≥ 2	4.50 pb	$^{+0.64}_{-0.57}$pb
≥ 3	0.655 pb	$^{+0.109}_{-0.105}$pb
≥ 4	0.157 pb	$^{+0.041}_{-0.028}$pb
≥ 5	0.1035 pb	$^{+0.0567}_{-0.0287}$pb

TABLE XIV

FINAL CROSS SECTIONS WITH JET RECO/ID ERRORS.

Jet Multiplicity	Cross Section	Jet Resolution Errors
≥ 1	29.6 pb	± 0.5 pb
≥ 2	4.50 pb	± 0.14 pb
≥ 3	0.655 pb	± 0.017 pb
≥ 4	0.151 pb	± 0.014 pb
≥ 5	0.1035 pb	± 0.0681 pb

TABLE XV

FINAL CROSS SECTIONS WITH JET RESOLUTION ERRORS.

We estimate the error due to the jet resolution smearing in the unsmearing procedure (Chapter 6.5.2.1) by varying the data jet resolution by $\pm$ 10%. Table XV summarizes the jet resolution errors.

Chi2 / ndf = 20.51 / 5
Prob = 0.001002
p0   = -3.148e-08 $\pm$ 2.748
p1   = 0.9498 $\pm$ 0.02305
p2   = 0.07017 $\pm$ 0.002726
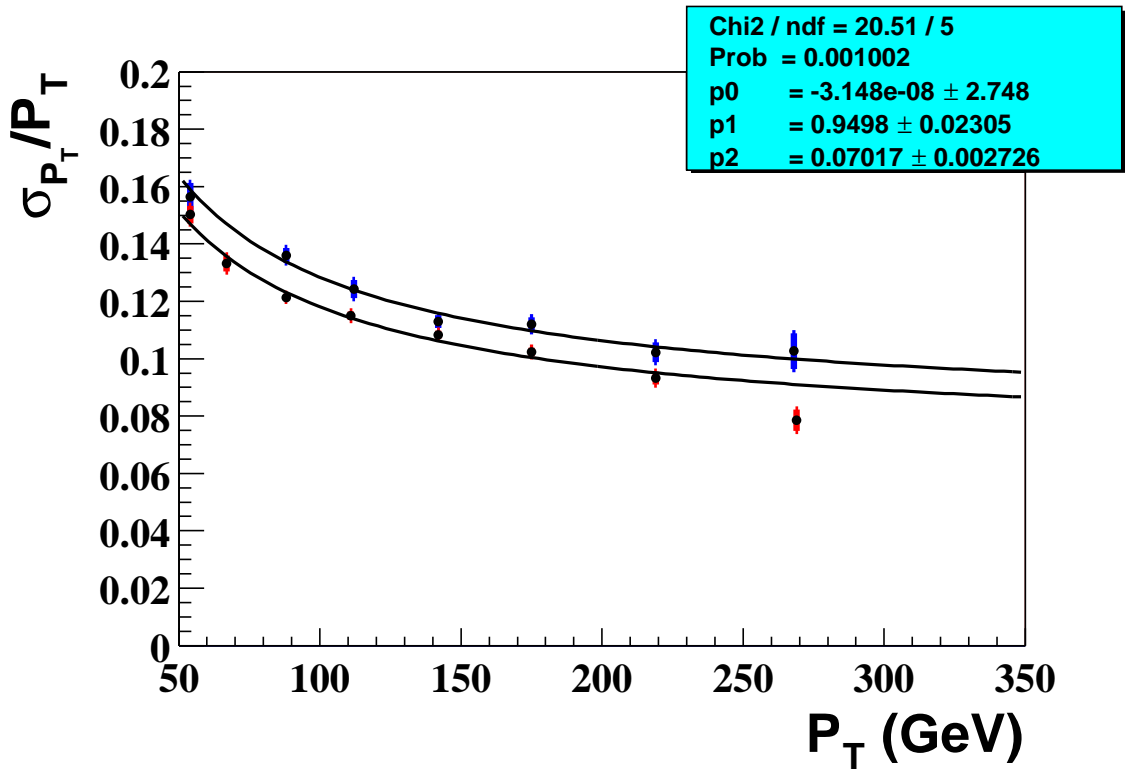
Figure 89. Comparing jet resolution for JES 5.1 (upper curve) and JES 5.3 (lower curve) in the central region of the Calorimeter. The difference is approximately 5% over the whole range.

Jet Multiplicity	Cross Section	Electron-jet-overlap Errors
≥ 1	29.6 pb	± 0.8 pb
≥ 2	4.50 pb	± 0.17 pb
≥ 3	0.655 pb	± 0.032 pb
≥ 4	0.151 pb	± 0.009 pb
≥ 5	0.1035 pb	± 0.0071 pb

TABLE XVI

FINAL CROSS SECTIONS WITH ELECTRON-JET-OVERLAP CUT UNCERTAINTIES.

6.6.3 Electron-Jet-Overlap Systematic Error

For each jet multiplicity we derive electron-jet-overlap correction factors using $\Delta R=0.4$ and $\Delta R=0.7$ rejection cones and then use the middle value as the final correction. The systematic error is the difference between the middle values and the correction factors derived with $\Delta R=0.4$ and $\Delta R=0.7$. Additionally we apply a linear fit to the final errors in order to compensate for statistical fluctuations.

Table XVI summarizes the systematic errors for the electron-jet-overlap cut.

6.6.4 Luminosity Systematic Error

The error due to the uncertainty in the luminosity measurement is 6.5% (14). Table XVII summarizes the luminosity errors.

Jet multiplicity	Cross Section	Luminosity Errors
≥ 0	248.9 pb	± 16.2 pb
≥ 1	29.6 pb	± 1.9 pb
≥ 2	4.50 pb	± 0.29 pb
≥ 3	0.655 pb	± 0.043 pb
≥ 4	0.151 pb	± 0.010 pb
≥ 5	0.1035 pb	± 0.0067 pb

TABLE XVII

FINAL CROSS SECTIONS WITH LUMINOSITY ERRORS.

6.6.5 Systematic Errors due to Efficiencies

In the following we take the systematic uncertainties of the object based efficiencies from Chapters 6.5.1.1 to 6.5.1.3, convert them into event based systematic uncertainties, and then propagate those uncertainties to the cross sections.

6.6.5.1 Trigger Efficiency

We estimate a relative systematic error of $\pm 1\%$ due to the variations in the trigger efficiencies versus jet multiplicity (see Chapter 6.5.1.1):

$$\varepsilon_{Object}(\text{pre-v12, inclusive sample}) = 94.6\%, \quad \delta\varepsilon_{Object} = 5\% \tag{6.12}$$

$$\varepsilon_{Event} = 2 \cdot \varepsilon_{Object} - \varepsilon_{Object}^2 = 99.7\% \tag{6.13}$$

$$\varepsilon_{Event}(-1\sigma) = 2 \cdot (\varepsilon_{Object} - \delta\varepsilon_{Object}) - (\varepsilon_{Object} - \delta\varepsilon_{Object})^2 = 98.9\% \tag{6.14}$$

$$\text{Relative Error} = \frac{99.7\% - 98.9\%}{99.7\%} = 0.8\% \approx 1\% \tag{6.15}$$

6.6.5.2   EM Reconstruction and Identification Efficiency

We estimate a relative systematic error of $\pm 7\%$ due to the variations in the EM reco and ID efficiencies versus jet multiplicity (see Chapter 6.5.1.2):

$$\varepsilon_{Object}(\text{data, inclusive sample}) = 88.9\%, \quad \delta\varepsilon_{Object} = 3\% \tag{6.16}$$

$$\varepsilon_{Event} = \varepsilon_{Object}^2 = 79.0\% \tag{6.17}$$

$$\varepsilon_{Event}(-1\sigma) = (\varepsilon_{Object} - \delta\varepsilon_{Object})^2 = 73.8\% \tag{6.18}$$

$$\text{Relative Error} = \frac{79.0\% - 73.8\%}{79.0\%} = 6.6\% \approx 7\% \tag{6.19}$$

6.6.5.3   EM-Track Match Efficiency

Table XVIII summarizes the relative systematic uncertainties due to the variations in the EM-Track matching efficiencies versus jet multiplicity (see Chapter 6.5.1.3). We estimate the uncertainties based on the following equations:

$$\varepsilon_{Object}(\text{data, n-jet sample}) = \varepsilon_n, \quad \delta\varepsilon_{Object}(\text{data, n-jet sample}) = \delta\varepsilon_n \tag{6.20}$$

$$\varepsilon_{Event} = 2 \cdot \varepsilon_n - \varepsilon_n^2 \tag{6.21}$$

$$\varepsilon_{Event}(-1\sigma) = 2 \cdot (\varepsilon_n - \delta\varepsilon_n) - (\varepsilon_n - \delta\varepsilon_n)^2 \tag{6.22}$$

Jet Multiplicity	Relative Error
≥ 1	0.5%
≥ 2	1.5%
≥ 3	2.3%
≥ 4	3.7%
≥ 5	5.5%

TABLE XVIII

RELATIVE ERRORS DUE TO UNCERTAINTY IN EM-TRACK MATCHING
EFFICIENCIES.

$$\text{Relative Error} = \frac{\varepsilon_{Event} - \varepsilon_{Event}(-1\sigma)}{\varepsilon_{Event}} \qquad (6.23)$$

6.6.5.4 Overall Efficiency Systematic Error

Table XIX summarizes the overall systematic error due to the efficiencies after adding all contributions in quadrature.

6.6.6 Jet Promotion Systematic Error

We study the effect of additional jets from multiple interactions within the same beam crossing, i.e. *jet promotion*. We compare jet multiplicities of events that have exactly one reconstructed primary vertex with events that have at least two reconstructed primary vertices (Table XX).

The two samples are normalized with respect to the number of events in the inclusive jet multiplicity bin. Initially the single vertex sample contains 7,848 events and the 2 (or more)

Jet Multiplicity	Cross Section	Efficiency Errors
≥ 1	29.6 pb	± 2.1 pb
≥ 2	4.50 pb	± 0.32 pb
≥ 3	0.655 pb	± 0.047 pb
≥ 4	0.151 pb	± 0.011 pb
≥ 5	0.1035 pb	± 0.0093 pb

TABLE XIX

OVERALL SYSTEMATIC UNCERTAINTIES DUE TO EFFICIENCIES (TRIGGER, EM, TRACKING).

vertex sample contains 5,900 events.

We conclude that the jet promotion effect is small since the discrepancy between the two samples is within the statistical error.

We also compare the average number of reconstructed primary vertices for different jet multiplicity samples (Table XXI) and don't see an effect within statistical errors.

6.6.7 Statistical Uncertainty

The statistical uncertainty has three contributions:

- We estimate the error due to the total number of corrected events δN_{corr} (corrected for Trigger, EM and Tracking inefficiencies) with the following Equation:

$$\delta N_{corr} = \sqrt{(w_{average} \cdot \delta N_{uncorr})^2 + (N_{uncorr} \cdot \delta w_{average})^2} \qquad (6.24)$$

Jet multiplicity	Exactly one primary vertex	At least two primary vertices
≥ 0	5,900	5,900
≥ 1	705	696
≥ 2	92	97
≥ 3	11	16
≥ 4	3	1
≥ 5	1	1

TABLE XX

NUMBER OF EVENTS FOR DIFFERENT INCLUSIVE JET MULTIPLICITIES WHEN REQUIRING EXACTLY ONE RECONSTRUCTED PRIMARY VERTEX AND AT LEAST TWO RECONSTRUCTED PRIMARY VERTICES. ENTRIES ARE NORMALIZED WITH RESPECT TO THE 2 VERTEX SAMPLE.

Jet multiplicity	Average number of primary vertices
≥ 1	1.583 ± 0.852
≥ 2	1.622 ± 0.911
≥ 3	1.733 ± 0.814
≥ 4	1.4 ± 0.8
≥ 5	2.0 ± 1.0

TABLE XXI

AVERAGE NUMBER OF RECONSTRUCTED PRIMARY VERTICES FOR DIFFERENT JET MULTIPLICITIES.

where N_{corr} is the total number of corrected events, N_{uncorr} is the total number of uncorrected events, and $w_{average}$ is the average weight used to correct for EM, Trigger and Tracking inefficiencies ($\approx$1.36).

- We estimate the error due to the number of background events δB by fitting an exponential function $a \cdot exp(b \cdot x)$ to the measured number of QCD events (Figure 90) and then using the error due to the two fitting parameters a and b as the uncertainty. The error of the exponential fit takes into account that the fitting parameters a and b are correlated:

$$f(x) = a \cdot exp(b \cdot x) \tag{6.25}$$

$$\delta f(x) = \sqrt{\left(\frac{\partial f}{\partial a} \cdot \delta a\right)^2 + \left(\frac{\partial f}{\partial b} \cdot \delta b\right)^2 + 2 \cdot \frac{\partial f}{\partial a} \cdot \frac{\partial f}{\partial b} \cdot covariance(a,b)} \tag{6.26}$$

- We add an additional error due to the statistical uncertainty of the acceptances (see Table IX).

- We add the statistical uncertainty due to the unsmearing and jet reco/ID coefficients (see Chapter 6.5.2.1).

Table XXII summarizes the statistical errors.
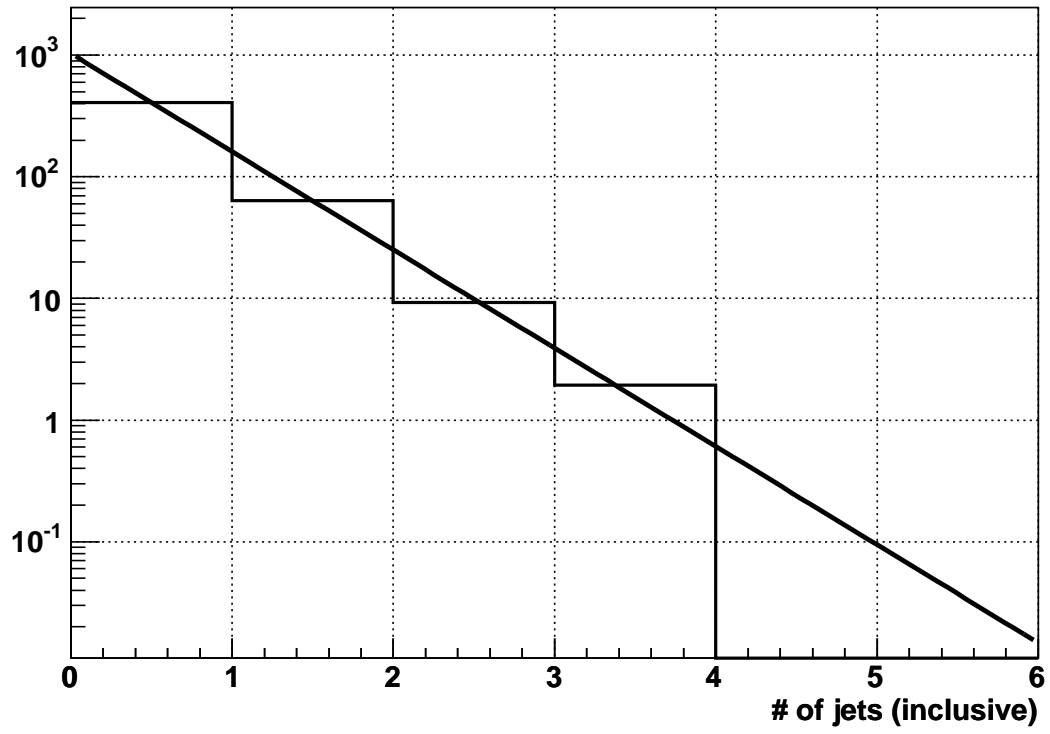
Figure 90. Exponential fit to the number of QCD events for different inclusive jet multiplicities.

Jet Multiplicity	Cross Section	Statistical Uncertainty
≥ 0	248.9 pb	± 2.5 pb
≥ 1	29.6 pb	± 0.8 pb
≥ 2	4.50 pb	± 0.32 pb
≥ 3	0.655 pb	± 0.129 pb
≥ 4	0.151 pb	± 0.070 pb
≥ 5	0.1035 pb	± 0.0738 pb

TABLE XXII

CROSS SECTIONS WITH STATISTICAL ERRORS.

CHAPTER 7

CONCLUSIONS

7.1 Final Cross Sections

The final cross sections for the 0-jet through 5-jet samples are summarized in Table XXIII. Figure 91 and Table XXIV compare our measured cross sections with theoretical values from MCFM (47) and CKKW MC samples (48). The MCFM jet cuts were chosen to be the same as in this analysis (jet $p_T > 20$ GeV, $|\eta| < 2.5$). The Z boson had a mass between 80 GeV and 100 GeV and CTEQ6M was used for the PDF. For MCFM the renormalization and factorization scales were set to $\mu^2_{F/R} = M^2_Z + p^2_{TZ}$.

For the CKKW samples a matching threshold of $p_T > 15$ GeV was chosen ($|\eta| < 2.5$) and the Z boson had a mass between 75 GeV and 105 GeV. The CKKW cross sections are normalized with respect to the measured cross section for the 1-jet sample. The matrix element generation of the CKKW samples (Madgraph (49)) was done up to jet multiplicities of 3. Higher jet multiplicities are due to parton showering and hadronization simulated with PYTHIA. For CKKW the factorization scale was set to $\mu^2_F = M^2_Z$. The renormalization scale was set to $\mu^2_R = p^2_{Tjet}$ for jets from initial state radiation and $\mu^2_R = k^2_{Tjet}$ for jets from final state radiation.

Figure 92 and Table XXV summarize the cross section ratios, i.e. normalizing the n-jet cross sections with respect to the inclusive cross section. All systematic uncertainties listed in

Jet Multiplicity	# of Signal Events	$Z/\gamma^* \to e^+e^- + \geq n$ Jet Cross Section
≥ 0	18,263.8	248.9 pb ± 2.5(stat) ± 16.2(lumi)
≥ 1	2,550.7	29.6 pb ± 0.81(stat) $^{+4.3}_{-4.0}$(sys) ± 1.9(lumi)
≥ 2	391.9	4.50 pb ± 0.32(stat) $^{+1.1}_{-1.1}$(sys) ± 0.29(lumi)
≥ 3	63.6	0.655 pb ± 0.13(stat) $^{+0.22}_{-0.22}$(sys) ± 0.043(lumi)
≥ 4	15.3	0.151 pb ± 0.070(stat) $^{+0.072}_{-0.066}$(sys) ± 0.010(lumi)
≥ 5	6.8	0.104 pb ± 0.074(stat) $^{+0.10}_{-0.06}$(sys) ± 0.0067(lumi)

TABLE XXIII

CROSS SECTIONS FOR DIFFERENT INCLUSIVE JET MULTIPLICITIES. NUMBER OF
SIGNAL EVENT ENTRIES HAVE UNSMEARING, JET RECO/ID AND
ELECTRON-JET-OVERLAP CORRECTIONS APPLIED.

Table XXV (except for the luminosity uncertainty) contribute to the cross section ratios R_n as

shown in the following equation:

$$\delta R_n = \frac{\delta \sigma_n}{\sigma_0}, \quad \text{with} \quad \sigma_0 = 248.9pb. \tag{7.1}$$

Figure 93 compares jet p_T distributions for different jet multiplicities between data and MC

(ALPGEN+PYTHIA). For ALPGEN+PYTHIA the renormalization and factorization scales

were set to $\mu^2_{F/R} = M_Z^2 + \sum p^2_{Tjet}$.

We find our results to be in good agreement with QCD predictions.
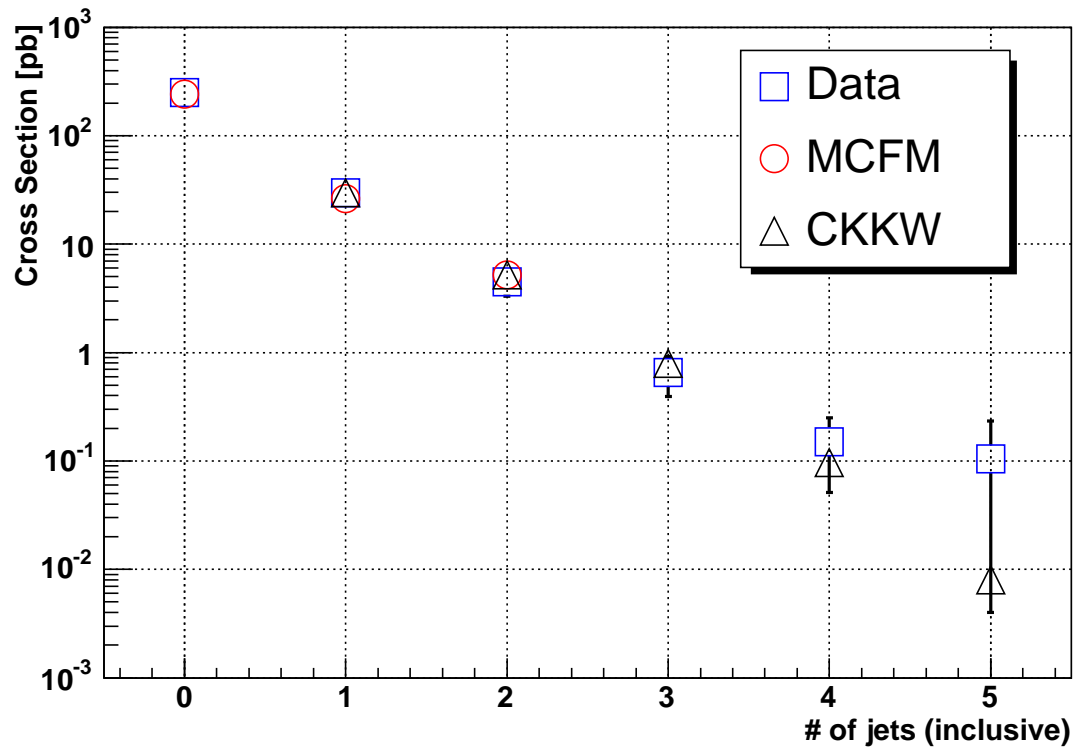
Figure 91. Cross sections for inclusive jet multiplicities in data (with total errors) compared with MCFM and CKKW.

Jet Multiplicity	Measured Cross Section	MCFM	CKKW
≥ 0	248.9 pb ± 16.4(tot)	241.5 pb ± 0.1(stat)	-
≥ 1	29.6 pb $^{+4.8}_{-4.6}$(tot)	26.2 pb ± 0.044(stat)	29.6 pb
≥ 2	4.50 pb $^{+1.2}_{-1.2}$(tot)	5.21 pb ± 0.069(stat)	5.22 pb
≥ 3	0.655 pb $^{+0.26}_{-0.26}$(tot)	-	0.798 pb
≥ 4	0.151 pb $^{+0.10}_{-0.10}$(tot)	-	0.096 pb
≥ 5	0.104 pb $^{+0.13}_{-0.10}$(tot)	-	0.008 pb

TABLE XXIV

COMPARING MEASURED CROSS SECTIONS WITH RESULTS FROM MCFM AND CKKW.

Jet multiplicity	$\frac{\sigma(Z/\gamma^* \to e^+ e^- + \geq nJets)}{\sigma_{Z/\gamma^*}}$ $[\cdot 10^{-3}]$	MCFM	CKKW
≥ 1	119.1 ± 3.3(stat) $^{+17.2}_{-16.2}$(sys)	108.4	119.1
≥ 2	18.1 ± 1.3(stat) $^{+4.5}_{-4.3}$(sys)	21.6	21.0
≥ 3	2.6 ± 0.52(stat) $^{+0.90}_{-0.89}$(sys)	-	3.2
≥ 4	0.61 ± 0.28(stat) $^{+0.29}_{-0.27}$(sys)	-	0.39
≥ 5	0.42 ± 0.30(stat) $^{+0.42}_{-0.24}$(sys)	-	0.03

TABLE XXV

COMPARING MEASURED CROSS SECTION RATIOS WITH RESULTS FROM MCFM AND CKKW.
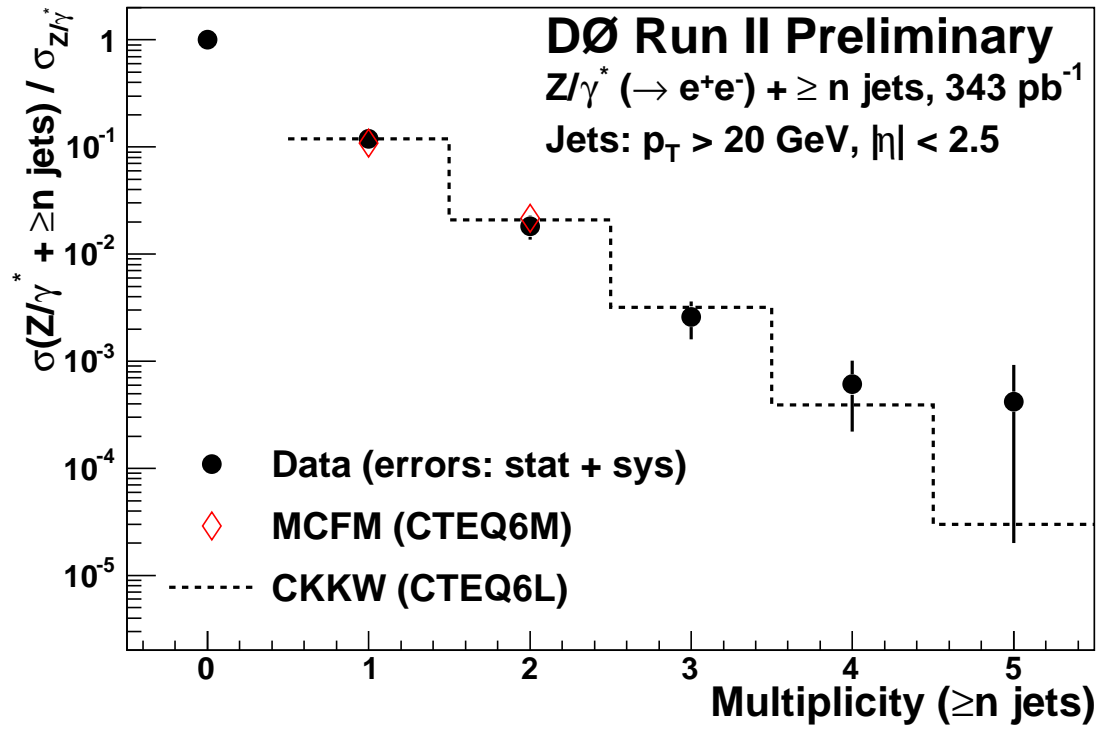
Figure 92. Ratios of the $Z/\gamma^*(\to e^+e^-)+ \geq n$ jet cross sections to the total inclusive $Z/\gamma^* \to e^+e^-$ cross section versus n. The errors on the data include the combined statistical and systematic uncertainties. The line (CKKW) represents the predictions of LO Matrix Element calculations using PYTHIA for parton showering and hadronization, normalized to the measured $Z/\gamma^*+ \geq 1$ jet cross section ratio. The open circles represent the MCFM predictions.
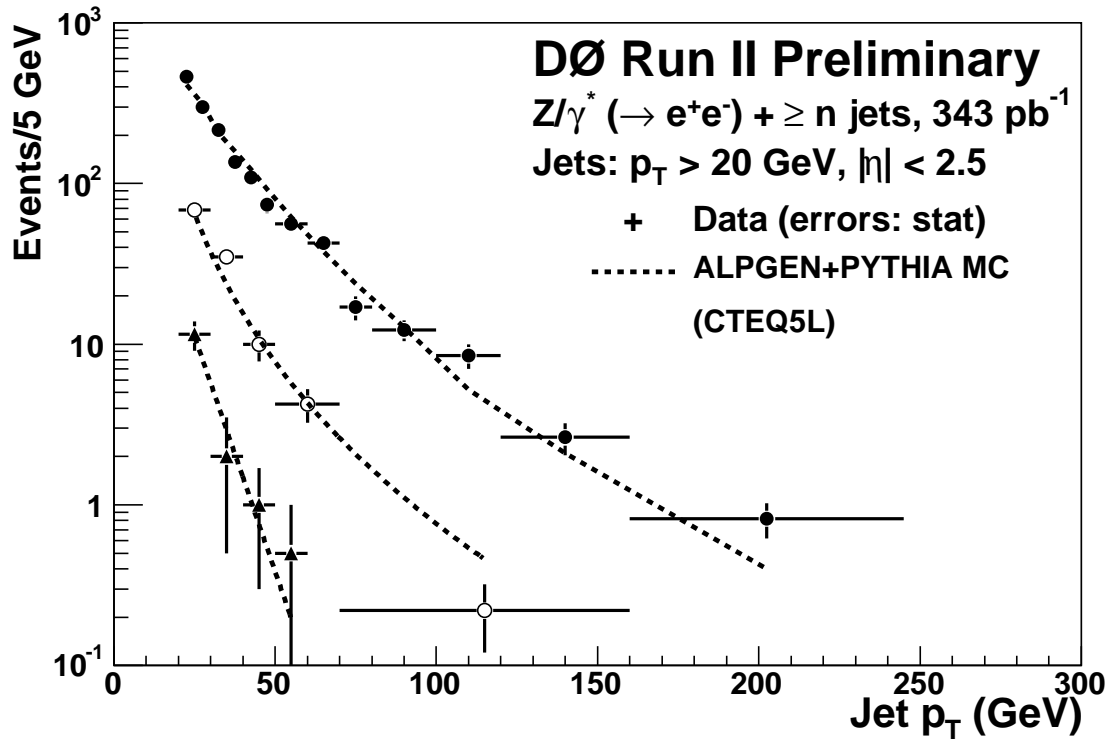
Figure 93. Data to theory (ALPGEN+PYTHIA) comparison for the highest p_T jet distribution in the $Z+ \geq 1$ jet sample, for the second highest p_T jet distribution in the $Z+ \geq 2$ jet sample and for the third highest p_T jet distribution in the $Z+ \geq 3$ jet sample. The errors on the data are only statistical.

7.2   Comparisons to other measurements

Using the inclusive PYTHIA MC sample we derive correction factors which allow us to estimate the Z/γ^* inclusive cross section for different diem invariant mass windows [1]. To calculate the correction factors we count the number of Z/γ^* candidates at the particle level within different diem invariant mass ranges and take the ratio which yields the correction that is needed to account for the change in the diem invariant mass range.

Using the cross section ratio between the inclusive Z/γ^* cross section and the inclusive Z cross section in MC, we derive another correction factor which allows us to convert the measured inclusive Z/γ^* cross section into the inclusive Z cross section (50).

Table XXVI lists our inclusive Z/γ^* cross section for different mass ranges, as well as the conversion into the inclusive cross section for pure Z boson exchange. We compare result (b) with the CDF measurement (51) for the inclusive Z/γ^* cross section (66 GeV $< M_{ee} <$ 116 GeV): 255.8 pb $\pm$3.9(stat).

7.3   Future Plans

A list and discussion of some of the things that we're planning to do for the publication.

---

[1] The MC sample used a generator cut of $|\eta_Z| <$4.2. Although no restriction in η_Z would have been preferable, we do not believe that it has a big impact on the final results.

Process	Mass Range	Conversion
(a) Z/γ^*	75 GeV $< M_{ee} <$ 105 GeV	248.9 pb
(b) Z/γ^*	66 GeV $< M_{ee} <$ 116 GeV	248.9 pb $\cdot\frac{392,174}{379,255} = 257.4$ pb
(c) Z/γ^*	60 GeV $< M_{ee} <$ 130 GeV	248.9 pb $\cdot\frac{400,000}{379,255} = 262.5$ pb
(d) Z	60 GeV $< M_{ee} <$ 130 GeV	248.9 pb $\cdot\frac{1.852}{1.869\cdot0.948} = 260.2$ pb

TABLE XXVI

CROSS SECTION RESULTS FOR DIFFERENT DIEM INVARIANT MASS RANGES AND PROCESSES.

APPENDICES

Appendix A

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Appendix B

THE LEVEL 2 TRIGGER SYSTEM AND ALPHA BOARDS

Level 2 is an essential part of the DØ trigger and data acquisition system (52), (53), (54), (55). It was designed to provide a reduction in the event rate by a factor of 10 within a 100 μsec time window while inducing less than 5% deadtime. As outlined in Chapter 3.4.2 the L2 trigger system is organized as a two-stage *stochastic pipeline*. In the first step (*preprocessing stage*) sub-detector based proto-objects are formed by preprocessors. The second step (*global processing*) combines the information provided by the preprocessors to make the event-wide L2 trigger decision. One advantage of this design is that each preprocessor is able to operate in parallel, independently from all other preprocessors. This allows to avoid deadtime since decision times can vary significantly from event to event. Additionally up to 16 events can be queued in buffers (*FIFOs*) between the stages. Figure 94 illustrates the relation between sub-detectors, and L1/L2 trigger elements.

B.1   The Standard Level 2 Crate

All L2 systems occupy 9U[1] VME crates (56):

- Forward Muon Preprocessor (L2MUF)

- Central Muon Preprocessor (L2MUC)

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[1]1U = 1.75 in
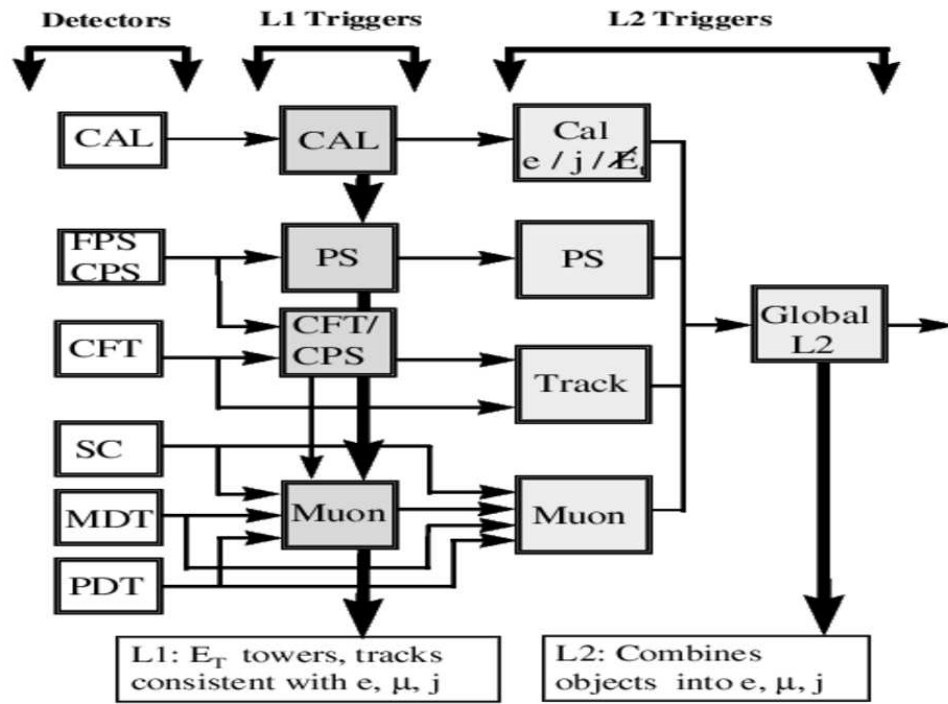
Figure 94. L1 and L2 trigger elements. Horizontal arrows are indicating the dataflow.

- Calorimeter Preprocessor (L2CAL)

- Preshower Preprocessor (L2PS)

- Tracking Preprocessor (L2CTT/L2STT)

- Global Processor (L2GBL)

Each crate contains a 64-bit VME bus (57) and a custom-built high-speed bus (*Magic Bus*, or MBus) for data-handling on an auxiliary backplane (58). The 128 bit MBus supports data rates of up to 320 Mbit/s. Figure 95 shows a schematic view of the L2CAL crate with its main components:

MPM (*Multi Port Memory*): A Bit3 MPM card is used as the VME crate controller. It downloads run-time parameters and reports monitoring data to the Trigger Control Computer (TCC[1]).

VBD (*VME Buffer Driver*): A VBD card is used to write data to the L3 system. The VBD cards were later replaced by VME single board computers (SBC).

Workers/Administrator (*Alpha Boards*): The Alpha Boards perform the main processing step within the L2 trigger system. Their main purpose is the application of the L2 trigger algorithms (*Worker*). They also handle additional event processing and local trigger control tasks (*Administrator*). A detailed overview of the Alpha Board system architecture is given in Chapter B.2. The Alpha Boards were later substituted by *Beta Boards* (59).

---

[1]TCC handles run control, downloads run-specific information, and collects monitoring data.

MBT (*Magic Bus Transceiver*): The MBT cards (60) receive L1 information and broad-
cast it to the Worker/Administrator via the MBus. After preprocessing is finished, the
outputs are sent to the L2 Global Processor (L2GBL). The MBT cards also receive infor-
mation regarding L1 trigger accepts, L2 trigger decisions, and system-wide initializations
(*Serial Command Link Initialize*, or SCLinit). Depending on the processing load addi-
tional *Assistant MBTs* can be added to the *Pilot MBT*.

Specialized hardware: In some cases additional specialized hardware for data conversion and
processing is added. In the case of the L2CAL crate the L1 input signals arrive in the form
of fiber-optic cables. A special converter card (*Fiber Input Converter*, or FIC) translates
optical into electrical signals (61).

B.2   Level 2 Alpha Processors

The overall design of the Alpha Board (Figure 96, Reference (62)) is based on the layout
of the DEC [1] PC164 motherboard (63). It features a 500 MHz Alpha CPU running under
real-time Linux. In addition to the internal PCI bus several elements supporting VME and
MBus interfaces have been added. Figure 97 shows a schematic view of the Alpha Board. The
main components are described in the following.

B.2.1   PC164 Based Design

The Alpha Board uses the first commercially available 64-bit RISC processor: a 500 MHz
Alpha 21164 CPU (64), (65). It can execute 2-4 instructions per cycle. The 500 MHz CPU

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[1]Digital Equipment Corp. merged with Compaq Computer Corp. in 1998.
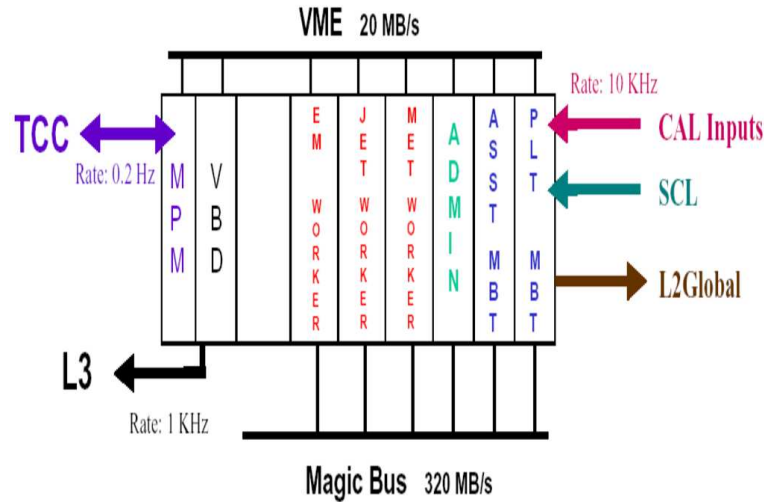
Figure 95. Layout of Level 2 calorimeter (L2CAL) crate with main components.

frequency is generated by a 50 MHz oscillator by means of a divide-by-10 phase-locked loop circuit.

The Alpha Board has several caches implemented, both onchip (integrated into the CPU) and external. 8 kB data and instruction caches (Dcache and Icache, respectively) buffer the most frequently used data and instructions to speed up processing. A secondary onchip 96 kB mixed data and instruction cache (Scache) is also used. A third level of external cache (4 MB) is not being utilized.

An interface between the CPU, main memory, and the PCI bus is provided by the 21172 Core Logic Chipset (Figure 98, Reference (66)). The 21172 Chipset consists of the 21172-CA chip (CIA) which provides the interface between the CPU and the PCI bus. It also provides
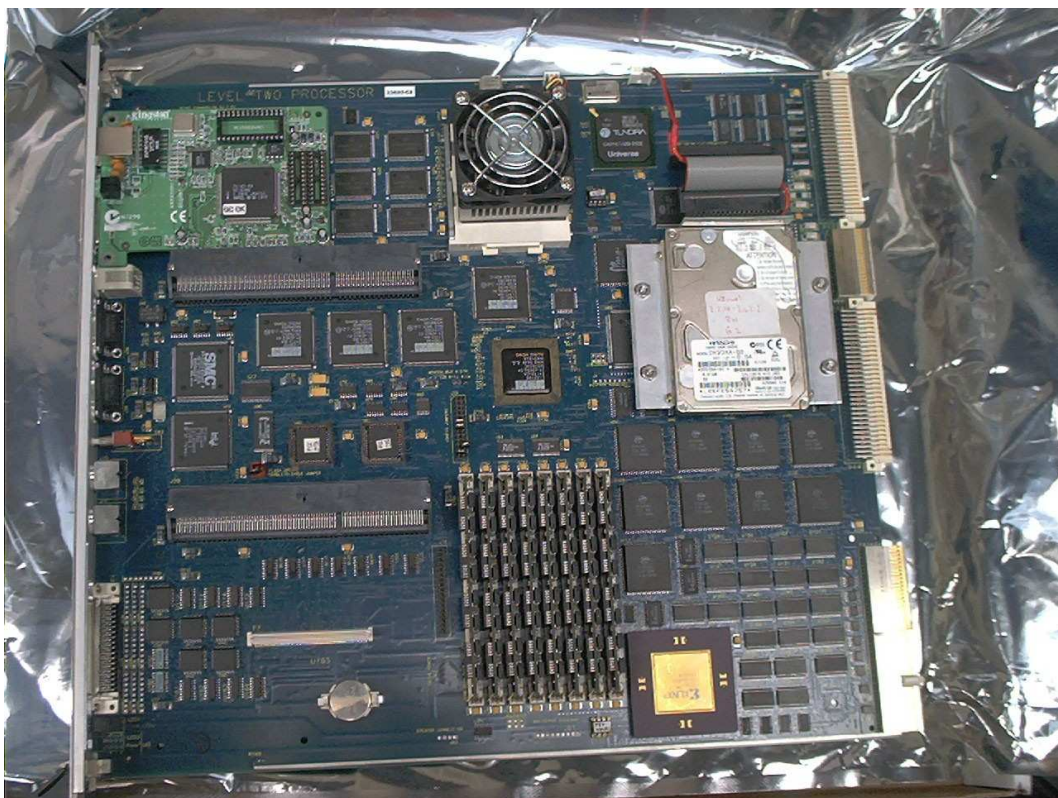
Figure 96. Level 2 Alpha Board with Ethernet card and hard disk drive.
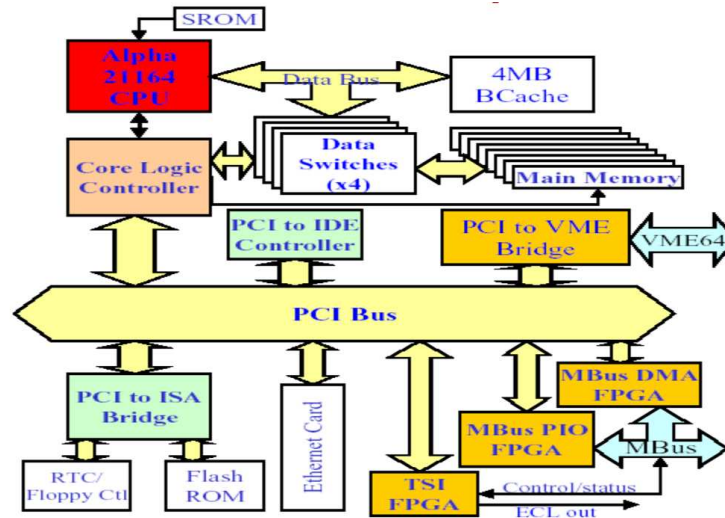
Figure 97. Block diagram of Level 2 Alpha Board.

main memory controlling and addressing capabilities. A set of four data switching chips (DSW)

functions as a multiplexing/demultiplexing device for main memory access. The 21172 Chipset

provides data transfer rate of up to 267 MB/s (64-bit at 30 ns/cycle).

The Alpha Board carries two kinds of firmware. A 128 kB SROM chip is directly connected

to the Icache. It contains the boot code that is loaded into the CPU at power-up, including the

initialization of the PCI bus, the setting of registers in the CIA, the setting up of the various

caches and memory, and finally the copying of the contents of the Flash ROM to memory. The

1 MB Flash ROM chip contain OS and task specific instructions. This includes instructions to

download user code via a PCI Ethernet card, a rudimentary local debugger ("Debug Monitor"),

and the server for a remote debugger. The SROM chip is installed in a socket, and can therefore

be programmed by using an external device programmer. The Flash ROM chip is soldered to the board, and must be programmed in situ.

A bank of eight SIMM slots provides 128 MB of DRAM memory.

The 64-bit 33 MHz PCI bus has two expansion slots. A standard PCI Ethernet card connected to one of the PCI slots is used for remote access. Two programmable chips (PLDs) are used for PCI interrupt handling and bus arbitration.

A PCI-IDE interface chip allows to connect a 6 GB IDE hard disk drive, which has real-time Linux installed.

A PCI-ISA bridge provides support for external devices such as mouse, keyboard, and floppy drive. It also supports a parallel port, two serial ports, and a real time clock. The ISA bus is used to access the Flash ROM.

B.2.2   Magic Bus Programmed Input/Output

An interface between MBus and PCI bus is provided by the Magic Bus Programmed I/O chip (MBusPIO). It allows to read and write data between the two address spaces and thereby provides a way of communication between different cards that are connected to the MBus. For example, a board connected to the MBus can write or read into Alpha Board memory. A programmable Xilinx XC4036EX chip (MAGICFPGA) is used for this task.

B.2.3   Magic Bus Direct Memory Access Interface

In order to boost processing time, data is transferred to and from Alpha Board memory by direct memory access (DMA), i.e. data on the MBus goes directly to Alpha Board memory
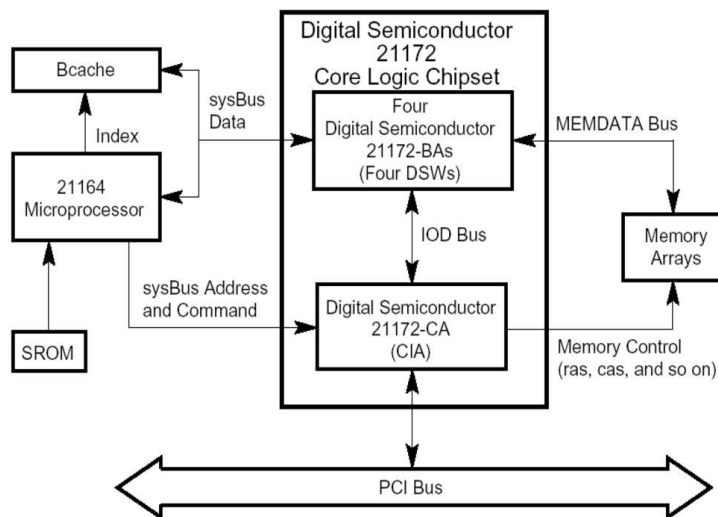
Figure 98. Block diagram of the 21172 Core Logic Chipset.

without involving the CPU. This *DMA engine* is implemented in two programmable chips: a Xilinx FPGA, and a Cypress CPLD.

B.2.4   VME Interface

A 64-bit PCI-VME interface is provided by the Tundra Universe II chip, by mapping "windows" of VME address space to Alpha Board memory space (67).

B.2.5   TSI Interface

The TSI interface is used to receive and send additional information to the trigger system. Is is also used to monitor the state of the Alpha Board processing elements.

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